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TEKTITES AND THEIR ORIGIN

by

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O'Keefe, relating to acknowledgments and copyright.

1. Pp. 279, 280: replace by new pages (attached). ✓
2. P. 376, under Table 6-4, after von Engelhardt, 1967,

insert

(Geochimica et Cosmochimica Acta, vol. 31, p. 1684,
1967. © Pergamon Press.)

3. P. 377, under Table 6-5, after Cuttitta et al, 1972, insert:

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4. Pp. 388-393: replace by new pages (attached). ✓
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From Chao, 1963 b (Tektites, Plate IId. © 1963 by the
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TEKTITE GLASS

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Tektites are pieces of natural glass, of sizes ranging from specks barely visible to the naked eye up to blocks the size of a football; they are usually black, but sometimes green or yellow. They have been treasured by those who found them, from modern aerodynamicists back to Stone Age hunters of the mastodon and the mammoth; interest in tektites is thousands of years older than interest in gold or silver.

The question is, where do they come from?

According to a careful sounding of forty lunar scientists, carried out by I.I. Mitroff (1974), the opinion that tektites come from the earth has a credibility between 70 and 75 percent; i.e. the collective opinion of these men is that the odds are between two to one and three to one in favor of a terrestrial origin.

On the other hand, among the persons who have spent the most time on tektites, opinion favors an extraterrestrial origin, by a somewhat narrower margin. V. Barnes, W. Gentner, and B. P. Glass would favor a terrestrial origin, while G. Baker, D. R. Chapman, E. C. T. Chao, G. H. R. von Koenigswald, and I would favor an extraterrestrial origin.

Despite this appearance of deadlock, I believe that the question is capable of a logical solution from the existing data.

PREFACE

Clearly the first step is to recapitulate the existing information. There are now around 900 papers in the literature; I have read almost everyone.

In the first seven chapters of this book, the available observations on tektites are summarized. I have begun with a chapter on the history of the problem, because this permits the reader to see the reasons why certain assumptions about the problem became established.

Thereafter, the treatment goes from the large to the small: the geographic distribution (Chapter 2), the external forms (Chapter 3), the microscopic studies (Chapter 4), the physical properties (Chapter 5), the chemical compositions (Chapter 6), and the nuclear properties (Chapter 7).

The information is found in an exceptionally wide range of sources in the literature. The structure of the strewn fields is partly in oceanographic literature, partly in Czech astronomical publications, and partly in the proceedings of the Royal Societies of South Australia, Victoria and Western Australia, as well as the usual geochemical and geophysical journals. A crucial remark about the general form of tektites is in the aerodynamic literature; the viscosity and certain thermal properties are also best stated in an aerodynamic study; the stress-optic coefficient is given

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N.B.
The complete
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PREFACE

in a study of thermal break-up; and the chemical abundances are scattered through hundreds of papers. Clearly the collecting and compiling of this information will be useful to future investigators, whether they agree with the conclusions of this book or not.

In chapters 8 and 9, I have studied the logical implications of the data. If I am not mistaken, the tektite problem presents to the theorist the ideal situation, in which it is possible to deduce conclusions which are, at the same time, rigorously logical and surprising. The paradox here is that although tektites are in some respects chemically more like common terrestrial rocks than like any lunar rocks (with some rare exceptions) yet the physical arguments force us, I believe, to reject a terrestrial origin for tektites. Other strong arguments force us to reject an origin outside the earth-moon system; these arguments have not been seriously questioned for the past 15 years.

We are thus led to accept a lunar origin for tektites, despite the fact that this seems, at first sight, incredible. In Chapter 10, the consequences of this conclusion are developed. Two unexpected results emerge:

a. Some lunar craters of considerable size must be the products of volcanism which occurred during the past few million years.

b. The moon must have within it, presumably at great depths, a reservoir of rock which is considerably more like the mantle of the earth than like the rocks from which the basalts of the lunar crust are derived. This result suggests strongly that the moon was formed by the breakup of the earth, and that its outer layers were strongly heated and largely volatilized after the fission event.

These conclusions illustrate the significance of the tektite problem. They are certain to be attacked.

It was mentioned above that the conclusions described here represent a minority opinion. On the other hand, it may be noted that during the 1960's the hypothesis of the lunar origin of tektites was, directly or indirectly, responsible for unpopular but successful predictions of the moon's dryness and general lack of volatiles, of its lack of nickel and other noble metals, of differentiation and volcanism in the moon, and of the presence of iron-rich basalts. Perhaps the conclusions of the present study will also work out.

Finally, let us note that tektites of some types are so abundant that if the conclusions of this book are correct, then anyone can go to the lapidary and, for the price of a restaurant meal, buy himself a piece of the moon.

CHAPTER 1

DEFINITION AND HISTORICAL INTRODUCTION

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DEFINITION

A tektite is a natural glass, usually black, but sometimes green, brown or gray, which occurs in lumps, usually a few centimeters in length, having no chemical relation to the local bed rock. Tektites are broadly similar to some terrestrial volcanic glasses (obsidians); they can be distinguished by heating to the melting point with a blowpipe or a blowtorch. Obsidians turn to a foamy glass, while tektites produce a few bubbles at most, because of their much lower content of water and other volatiles. Under the microscope, obsidians are seen to have abundant micro-lites (microscopic crystals); tektites have essentially none.

Tektites are not found as isolated objects; they are found as members of large associations, called strewn fields,^(See Fig. 2.1) whose extent varies from a kilometer or so to 10,000 kilometers.

Associated with the macroscopic tektites in a strewn field there is a considerably larger mass (at least in many cases) of microtektites, ranging in size from 1 millimeter to the limit of detectability (currently about 40 microns).

The word tektite was coined by F.E. Suess (1900) from

DEFINITION AND HISTORICAL INTRODUCTION

the Greek $\tau\eta\kappa\tau\omicron\varsigma$, meaning molten.

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HISTORICAL INTRODUCTION

Early studies; the question of the mother lode

The first human beings known to have interested themselves in tektites were Cro-Magnon men of the Aurignacian period (Bayer, 1918). A few splinters of tektite glass were found at Willendorf, in Austria, in the same site as the famous statuette of the Venus of Willendorf (Pl. 1). The fragments had been chipped, like thousands of flint tools found nearby. The date of the Venus of Willendorf is given by Nougier (1966) as 29,000 B.C., or, as we shall write it, -29,000 yrs. A similar age of -10,000 to -20,000 yrs was found for some flaked tools of Libyan Desert glass (Oakley, 1952), see Plate 2.

In the Philippines, according to Beyer (1934 a, b) tektites were flaked into tools by pre-Neolithic man starting not later than -4000 to -6000. In the Iron Age (after -500) they were also carried around, as if for amulets. Busick (1937) remarks that practically all Philippine and Malaysian peoples

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of Middle and New Stone Age manufactured tools from tektite glass.

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In Indochina, tektites were found associated with Neolithic pottery (Lacroix, 1931 a). A large block of tektite glass was buried along with some quartz crystals in the sacred receptacle under an idol at Chom Khsan, some time in the Angkor Wat period of Khmer civilization (Lacroix, 1930). A similar deposit was found at Kompong Speu (Lacroix, 1935 c).

In modern times they have been used by European jewelers (Suess, 1900), Vietnamese (Lacroix, 1934 a); Siamese (Lacroix, 1934 a, b), natives of the Ivory Coast (Lacroix, 1934 b), Texas farmers (Barnes, 1939) and Australian aborigines (Baker, 1959 b) ^{P₂, P₃} (Pl. 3).

The precise names used by the local people are of great importance to anyone wishing to collect tektites; a list is given by Barnes (1959).

The first written reference to tektites is by Liu Sun, about 950 A.D. (Lee Da-ming, 1963, translated by C.S. Peng, and abstracted by Barnes, 1969), who notes that they are called lei-gong-mo, and are collected in the fields after sudden rainstorms in Leichow. Lee therefore proposes that all tektites from China be called lei-gong-mo.

The long history of human interest in tektites, including

the prehistoric use of them, is important because in all this immense span of time, no one seems to have found an outcrop of tektite glass. (By contrast, obsidian from the volcanic rock of the Lipari islands was an important item of Neolithic trade.) Instead, tektites are always found as float, i. e. detached pieces. Josef Mayer remarked, in the first known European description of tektites (1787, quoted in Suess, 1900) that no one has ever found the Mutterstein (mother lode). Several of the most significant things that have been found out about tektites are negative statements, and this is one of them.

The Czechoslovakian tektites, which were eventually named moldavites (after the Moldau River, in Bohemia, and not after the territory of Moldavia, in Rumania) were the subject of about 40 papers during the late 18th and 19th centuries, which are reviewed by Suess (1900). The tektites were then most often called Bouteillensteine (bottle-stones); the question of natural vs artificial origin was debated.

The first scientific reference to the Australian tektites is (1844) Fig. 1-1 *is a drawing by* by Charles Darwin, the evolutionist. *Darwin.* Plate 4 shows the specimen ~~which he described, note the flange of glass around the circumference.~~ Darwin thought it was an obsidian, and attributed the flange to rapid rotation. Nineteenth century Australian references

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to tektites, under the name of obsidian bombs, are collected by Walcott (1898).

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The Libyan Desert glass seems to have been noted by French explorers; Spencer (1939) cites an 1850 memoir by Fresnel which refers to glass in this region.

Van Dijk (1879) described and photographed tektites from the island of Billiton in Indonesia. They were discovered in the course of mining for tin. Van Dijk's work is memorable for the fact that he drew attention to the similarity to Bouteillensteine, or moldavites.

In an important paper, Stelzner (1893 a) studied some Australian tektites sent him by Victor Streich, who had gone with the Elder expedition. In a private letter, Streich had apparently suggested that they were a kind of meteorite. Stelzner noted that they were similar to moldavites. He also saw that the curious flanged appearance of ^{some} Australian tektites, like ice-cream in a dish, ^(See Fig. 3-1) could be explained if they had begun as spheres and had been partly melted. The melt, moving backward as a result of air pressure, could produce the flange. The pits, grooves and notches found on many tektites he regarded as the result of attack by aerodynamic forces. He did not at first commit himself about their origin, but a little later (1893 b) he decided that they could not be of extra-

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terrestrial origin because glass is not found in meteorites.

Stelzner's ideas were taken a step further by ~~R. D. M.~~

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Verbeek (1897 a, b), who knew Stelzner. Verbeek joined the tektites of Billiton (the billitonites) to those of Australia (australites) and the moldavites, and suggested that all three were the ejecta of lunar volcanoes. He had studied the 1883 eruption of Krakatoa, and believed, probably incorrectly, that the eruption had sent out some rocks with velocities as great as 2.37 km s^{-1} , which is the escape velocity from the moon's gravitational field. Despite this weakness, it now appears possible that Verbeek's idea may be essentially right after all.

Verbeek's hypothesis was warmly received in Australia, probably chiefly on the basis of the report in Nature (Anonymous, 1897); ~~Many similar ideas were published by Twelvetees and~~ Petterd (1897) and Walcott (1898). In Europe, similar ideas were published by Krause (1898), Suess (1898) and Rzehak (1898).

Shortly afterward, F. E. Suess (1900), the second of the dynasty of Austrian geologists, brought out a fundamental memoir on the origin of moldavites. In this paper, the three types of glass are first brought together under the common name tektites, which Suess coined. Suess was thoroughly convinced, that tektites are extraterrestrial in origin. He attributed most of the sculpturing

of tektite surfaces to aerodynamic attack. With advice from Ernst Mach, then teaching at Vienna, Suess built a sort of wind tunnel, and simulated the aerodynamic ablation of glass, using rosin models, and a hot airstream from his brother's cement factory. Suess's main arguments remain valid today (see Ch. 3): His memoir was widely read; many authorities thereafter spoke of tektites as glass meteorites.

Artificial vs. natural origin

During the period from 1900 to the outbreak of World War I, the question of artificial vs. natural origin of tektites was debated. The moldavites, by an unfortunate coincidence, occur in a region which was a center of early European glass-making. Suess considered that they could not be artificial because the temperature required to melt moldavites is so high that from experiments run by the great authorities ^{Ernst} Abbe and ^{Otto} Schott, at the Zeiss works in Jena, it seemed clear that no furnaces earlier than the Siemens regenerative furnace could get high enough temperatures. Johnsen (1906) pointed out that artificial glasses can be distinguished from natural glasses, in general, by their low contents of Al_2O_3 , and their high contents of alkalis; these

differences account for the lower viscosity of artificial glasses.

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By this test, tektites are natural glasses.

A flurry of excitement was produced when Weinschenk (1908) brought forward two glass balls from Kuttenberg, which he claimed were moldavites. A crust on the outside he attributed to fusion in the atmosphere, like the crust seen on meteorites; this, he said, was proof of the correctness of Suess's ideas. Weinschenk's paper was attacked by Rzehak, (1912 a, b) who showed that the glass was typical of some early artificial glasses, although a little low in silica. He also showed that the crust was a porous material of low index of refraction (1.495 vs. 1.521 for the glass itself), and very resistant to melting. Highly silicic residues with these properties are found to be typical of weathered glass.

The meteoriticist F. Berwerth (1917) pointed out that tektites have a remarkably close chemical resemblance to sedimentary rocks, especially sandstones; this is a crucial point which has often been rediscovered. Berwerth went on to suggest that tektites were the product of an ancient human culture, extending all over the earth. This part of his argument did not convince people, particularly because Suess could already show (Suess, 1916) that tektites had existed as far back as the Aurignacian, which he knew to be earlier than -20,000 yrs. Berwerth's

paper was the last serious suggestion that tektites are artificial; the conclusion that they are not artificial is another of the important negative statements about the tektite problem.

Tektites as terrestrial volcanic rocks?

A more difficult question was the distinction between tektites and terrestrial volcanic rocks. The early Australian investigators W. Z. (Clarke, 1855, 1857, Stephens, 1898, Twelvetrees and Petterd, 1897, 1898) regarded tektites as obsidian bombs. Walcott (1898) and Suess (1900) pointed to the enormous distances between the tektite strewn fields and the nearest volcanoes. The possibility of distribution by the natives could not, however, be satisfactorily eliminated.

Merrill (1911) set the tone for many U.S. discussions of the tektite problem by saying that the markings on tektites do not differ essentially from those on obsidian (see also Buddhue, 1941).

~~E. J.~~ Dunn (1911, 1912a), on the other hand, noted the existence of large, nearly spherical internal bubbles in some tektites. He reasoned, correctly, that these tektites must have been formed, and must have hardened in some kind of fluid, since on a solid surface, the hollow sphere would promptly collapse.

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The fluid could not have been water, since the liquid lava would have exploded if plunged in water; it was therefore, Dunn argued, some kind of gas.

He then elaborated a unique idea of large, thin bubbles of obsidian, produced by lightning strokes in a dusty atmosphere filled with hot gases. He suggested that these bubbles might be formed during a volcanic eruption, and might be thin enough to float through the air for thousands of miles. Eventually, he believed, the bubbles broke up; the thin walls were completely destroyed. Nothing was left except the congealed drop at the bottom of the bubble (like the drop often seen at the bottom of a soap bubble); this, he thought, was the origin of the flanged australites. His photographs of sections of flanged australites are among the best ever made (Dunn, 1912 a).

Dunn's theory was criticized by Summers (1909, 1913), who pointed out that tektite compositions are unlike those of terrestrial volcanic rocks; in particular, tektites occupy very thinly-populated classes in the usual Cross, Iddings, Pirsson and Washington (CIPW) classification of igneous rocks. Summers also notes that the dust would have to be unbelievably thick. Ideas like those of Dunn, but starting from ordinary wind-blown dust were later put forward by F. Chapman (1933) and R. Vogt (1935). Vogt drew

attention to the remarkable similarity between tektites and loess (windblown deposits of dust). Nininger (1952) remarked that if this mechanism worked anywhere, it should have worked on the Great Plains, where dust storms and lightning often occur together; but ~~no tektites were found~~ in his searches, despite the examination of some 50,000 allegedly meteoritic specimens brought in by the general public, no tektites were found.

Suess (1914) restated the chemical differences between tektites and obsidians: tektites have more $\text{FeO} + \text{MgO}$, and less $\text{Na}_2\text{O} + \text{K}_2\text{O}$ than obsidians of the same silica content; also K_2O predominates over Na_2O . These chemical distinctions were reiterated by Mueller (1915), Suess (1916), Dittler (1933) and Loewinson-Lessing (1935). They have led to another generally accepted statement: tektites are not the products of terrestrial volcanism.

New discoveries of tektites, to 1918

In the meantime, tektites were discovered in new places. Scrivenor (1909, 1916) found them in Malaya, Java, Borneo and the Natuna archipelago. ^(See Fig 2-5) Hills (1915) reported a new kind of tektite, with SiO_2 up to 85 percent, found by Conder in Tasmania ^(see 2-4) (discovery described in Conder, 1934). Suess (1914) wanted to call

this queenstownite, but the name was already in use, and the name Darwin glass is therefore given, after Mt. Darwin, in Tasmania. The status of Darwin glass as a kind of tektite was debated for the next 60 years.

The interwar period

Theories of the 1920's

The First World War interrupted tektite research; when it recommenced, three remarkable new theories opened the discussion.

V. Goldschmidt (1921, 1924) proposed to explain tektites as the result of a collision between a meteorite and a "cosmolith" or natural earth satellite. The idea was not later referred to.

Easton (1921) suggested that tektites are produced by the drying-out of siliceous gels, resulting from the action of humic acid. Although the theory has not survived, his detailed discussion of the decorations (pits, grooves, navels, etc.) on billitonites is valuable. Like Suess, he noted the relation of sculpture to overall form. Basically, he objected to Suess's idea of extra-terrestrial origin because, he noted, a granitic shell would not be likely to exist on a planet; again, he asked, why not tektites in

historic times, while there are plenty of meteorites?

Easton's paper was rebutted effectively by van der Veen (1923) in another useful paper. Van der Veen found that X-ray diffraction patterns of gels indicate that they are really crystalline, despite the amorphous appearance; X-ray patterns for tektites indicate only amorphous structure. Van der Veen also pointed to the wide interval from softening to melting (800 - 1200 °C) as evidence of a glassy structure. He suggested that the major sculpturing of tektites may result from chemical enlargement of fine cracks, and that these in turn may result from thermal shock, an idea later confirmed by Centolanzi and Chapman (1967). These results seem to apply principally to the worm-track markings which are prominent in billitonites. Van der Veen noted some very delicate ornaments on billitonites (mushroom-shaped projections a few millimeters in size; see Plate ^{124, 5} 5) which could not, he felt, be expected to survive the fall to the ground, and must therefore be due to attack by ground chemicals.

Suess (1922) pointed out that Easton's idea would lead to a relation between soil type and tektite chemical composition, which is not observed; he also said that silica gels could not become as dry as tektites. Easton's idea is no longer considered.

Michel (1922, 1939) noted that Wahl had suggested that in

the hypothetical parent^t body from which meteorites come, the light metals might not be completely oxidized. He suggested that tektites might result from the burning of these light metals in the earth's atmosphere. This idea was supported by Suess (1933) and Lacroix (1934) and ^CFenner^{criticized} (1938). It was shot down by F. Watson (1935) ^(see also Fenner, 1938a) who calculated that the rate of penetration of heat into the interior of the mass would not permit the burning of the tektite during the relatively short period of flight in the earth's atmosphere. Watson pointed out that the Widmanstätten figures are observational evidence that heat does not penetrate deeply even in iron meteorites, which have a high thermal conductivity.

Hardcastle (1926) suggested that tektites are formed by the superficial heating of stony meteorites. He thought that aerodynamic forces might sweep off the liquid layer, and form it into drops. This idea has not been accepted in its original form, since stony meteorites are very different from tektites in chemical composition; but the more plausible idea that tektites might be ablation droplets from a larger body of tektite composition was formulated (independently of Hardcastle) by Hanuš^V (1928). It was taken up again in the 1960's and will be further discussed in Chapter 8.

David et al (1927) and de Boer (1929) independently pointed

out that all tektite occurrences known up to that time fell along a great circle. They suggested that tektites had come from a shoal of bodies in orbit around the earth. The idea was generally given up when Lacroix (1934)^b found tektites in the Ivory Coast, 45° of latitude off the proposed great circle. La Paz (1938) however then postulated two great circles, and when tektites were found in Texas by Barnes (1939) and Stenzel, he suggested (1944) three great circles.

An interesting extension of Verbeek's (1897)^{a, b} theory of tektite origin from lunar volcanoes was put forward by Linck (1928). Linck noted that the aerodynamic sculpturing of meteorites is not in general much like tektite sculpture; it tends to soften the features of the surface, while moldavite sculpture, and to a less extent, tektite sculpture in general, tends to be very sharp. He suggested that the sculpture may have been produced by the gases which expelled the tektites from lunar volcanoes. This idea remains defensible to the present.

New discoveries of tektites, 1920 - 1940

In this interwar period, the boundaries of the tektite strewn fields were rapidly extended. The tektites reported during the 1920's from South America have been shown to be volcanic, and

are not discussed here. But in 1926, H. Otley Beyer found some tektites at Novaliches, on the island of Luzon, in the Philippines. They were recognized as tektites by H. Overbeck, and an account was distributed in typewritten form (Beyer, 1962). Beyer subsequently collected a very large number of tektites -- on the order of one million -- from all over the Philippines. (Beyer 1962-7)

Soon after Beyer's discovery, Lacroix (1929)^a announced the discovery of tektites in Cambodia. Later (1930) he reported that tektites were to be found all over Indochina, from 21° to 7° North latitude, and from 103° to 121° East longitude. His research on the indochinites was summarized in an important memoir (Lacroix, 1932) which tended strongly to bridge the traditional gap between the billitonites and the australites. The memoir mentions tektites in China at Kwang-chow-wan.

In 1934, Lacroix reported the discovery of a completely new group of tektites in the Ivory Coast (Lacroix 1934 b, 1935 a). Unlike all other groups, the Ivory Coast tektites have more Na_2O (by weight percent) than K_2O .

Lacroix next found the tektites of the type now called Muong Nong type. These are found in the same areas as the indochinites, but they are larger and are blocky in overall shape. They show a layered structure, like a sedimentary rock, but chemically they

are nearly identical with the rounded tektites (called splash-form tektites by Barnes) from the same area. It was blocks of this Muong Nong type material that were treasured by the Khmers at Chom Khsan and Kampong Speu.

Clayton and Spencer (1934) reported on a transparent yellow-green glass, called Libyan Desert glass. The relation of this to the tektite problem is disputed; but in this book it is regarded as probable.

The first tektites identified in North America were brought to light during the Depression by a Works Projects Administration (WPA) project in April, 1936, and identified by H. B. Stenzel. They were described by Barnes (1939), who notes that they had been locally known for 50 years previously. He also mentions (p. 548) the identification of the first Georgia tektites by Oscar Monnig in a letter to E. P. Henderson.

Tektites were found in Java by von Koenigswald (1935) in the Trinil formation, which also yielded a skull of the hominid Pithecanthropus erectus and some mid-Pleistocene mammals.

Theoretical and laboratory work of the 1930's

In 1932, the explorer H. St. J. B. Philby (father of Kim

Philby, the Soviet agent), having embraced the Moslem faith, set out to explore the Rub' al Khali (the desert of SE Arabia). He was searching for a circle of rock in the sand which the Arabs considered to be the burned-out ruins of the Biblical treasure-city of Ophir, which the Arabs pronounce Wabar. He reached it, saw that it was some kind of crater, and brought back rock from the area. He secured the help of L. J. Spencer in studying it, and Spencer (1933 a) wrote an appendix to Philby's book, The Empty Quarter. Spencer perceived that Wabar was a meteorite

Spencer was led by this event to put forward an idea which he supported to the end of a long and influential career, namely, that tektites are the product of meteorite impacts like that at Wabar.

impact crater; he was especially interested in some silica-glass formed there from the desert sand by the heat and shock of the impact.

Spencer was led by this event to put forward an idea which he supported to the end of a long and influential career, namely that tektites are the product of meteorite impacts like that at Wabar. He noted a resemblance of Wabar glass to Darwin glass (Spencer, 1933 b) and even to indochinites, as shown in the papers of Lacroix. He was immediately attacked by Scri-

venor (1933) who pointed to the absence of partially fused rock or sand in tektites, and by Fenner (1933) who said that the slaggy masses from Wabar resembled tektites neither in form nor in composition. Spencer replied, referring to some glassy bombs from Wabar, which resemble tektites both in form and in composition. He and Hey (1933) described a similar glass from the meteorite impact crater at Henbury, in Australia. Suess (1933) abandoned his earlier opinion that Darwin glass is a tektite, but adhered to the extraterrestrial origin of other tektites. The controversy between Fenner and Spencer continued for the next twenty-five years.

Fenner wrote a series of papers (1935, 1937, 1938^a, 1940^a, 1949, 1955) on the distribution and morphology of australites (Australian tektites, not including Darwin glass) in which he developed the idea that the flanges which are observed on australites result from the flow of melted glass, and that the underlying shapes before ablation are those of a rotating liquid mass under surface tension. Except for the point about rotation, the ideas which he developed on the forms of australites have been generally accepted.

In Czechoslovakia, Janoschek (1934, 1936) studied the stratigraphic relations of the moldavites; he attributed the mol-

davites to the Helvetian, which in Central Europe is a subdivision of the middle Miocene; specifically, Janoschek connected the moldavites with layers containing the fossil Oncophora.

Since the Australasian tektites were already known or believed to be of Pleistocene age, this meant that the great-circle idea was wrong.

Martin (1934 a) and Koomans (1938) separated tektites from amerikanites (tektite-like obsidian bombs found in the Philippines, and originating from terrestrial volcanoes) on the basis of composition, especially water content. Martin felt that tektites form a clear petrological sequence: billitonite -- australite -- moldavite -- Darwin glass.

~~E~~ Preuss (1935) in his dissertation gave a very detailed analysis of some tektites by spectrographic analysis. He noted some broad regional trends in the Australasian strewn field: an inner region in southern Indochina and Billiton, and an outer region including north Indochina and Australia. These are distinguished by a difference in the abundance of Ni and Cr, which are enriched in the central zone. In this book the tektites of the central zone are called, following Chapman and Scheiber (1969)^b the high-magnesium clan.

Preuss further found that tektites are chemically much like

terrestrial sedimentary rocks, in particular a Norwegian loam. Tektites tend to differ, however, from the most nearly comparable terrestrial materials through excess of silica, deficiency of Na_2O , and deficiency of a number of elements on the right-hand side of the periodic table (Cu, Ge, Sn, Pb) which are volatile at temperatures around 1000°C . Preuss suggested that the differences are due to an episode of strong heating. Preuss's work has been confirmed to a remarkable degree by later studies (Taylor, 1966, Chapman, 1971). Heide (1936 b) concluded from Preuss's work that Spencer must be right. He later noted (1938b) that tektites from Thailand and the Philippines belong to the outer, nickel-poor zone of the Australasian strewn field.

During this period there was an active school of Czech students of tektites. Their work is inaccessible because of the language difficulty; it is summarized by ~~X~~ Kaspar (1938). Heey concludes that the microsculpturing of tektites is due to chemical corrosion, but the macrosculpturing is not. He notes that many tektites appear to be fragments of larger bodies which contained bubbles ^{Pl 6, 7} (~~Plate~~ 5). The bubble cavities are now broken open in most cases. The inner walls of the bubble cavities are found to be unsculptured, while the outer walls are heavily sculptured. Evidently the process of corrosion, whatever it was,

stopped before the bubbles were broken open. Most tektites were protected against breakage by burial in the ground during most of the time between fall and recovery. Hence the breakage probably occurred during the fall to the earth or shortly thereafter, prior to burial. Hence, Kaspar argued, the macrosculpture is not due to ground chemical attack. The paper of N. Oswald (1942) has been translated; it presents his strong opinion that the markings on moldavites can not be attributed to chemical attack after fall to the earth.

Volarovich and Leontieva (1939) measured the viscosity of tektite glass as a function of temperature; this work has been much used for physical theories.

Barnes (1939) suggested that tektites are fulgurites (glass produced by lightning striking the earth). This suggestion was criticized by Fenner (1949).

La Paz (1938) suggested that the very broad distribution of tektites, compared to the very restricted areas of individual meteorite falls, might indicate that they had moved in a low satellite orbit around the earth, like the great meteor procession of February 9, 1913 (the Cyrillids). The idea was supported by Fenner (1938 a) and later by O'Keefe (1958, 1963 b).

From World War II to Sputnik I

World War II halted most work on tektites, although George Baker's morphological studies (Baker, 1937, 1939, 1940, 1944, 1946, 1955a, 1956a,b, 1957, 1958a,b) continued through this time. An important memoir (Baker, 1944) confirmed Dunn's observation that some pits occur under the flanges of australites, and that these pits are infilled with glass from the flanges. These pits were therefore certainly not produced by ground chemicals. The same memoir notes the presence of bands of glass in australites with index of refraction up to 1.535.

In his Halley lecture, Paneth (1940) remarked that Michel's burning-light-metals idea will not work; the volume of oxygen demanded (at the relevant atmospheric heights) is too great.

Nininger (1940, 1943a,b, 1952) suggested that tektites originate by meteorite impact on the moon. His chief argument was that impacts must launch portions of the lunar surface at escape velocity; some of the debris must reach the earth. He argued that tektites are not found outside an equatorial belt some 90° in width. He considered (incorrectly, as it turned out) that this would result from the position of the moon's orbit. His hypothesis was supported by Kuiper (1953, 1954) who explained the composition of tektites as the result of a fractionation process: material driven off the earth at high temperatures condensed on the cool moon. Nininger's hypothesis is one of the important

ideas of the present day study of tektites.

Khan suggested (1947) that tektites are produced by the fall of anti-matter.

Cross (1948) brought forward some tektite-like glass bodies from Valverde County, Oklahoma; these were rejected as tektites by La Paz (1948) because they foam before the blowpipe, and contain crystals. They are presumably obsidians.

Fenner (1949) found that the anterior portion of australites has a tendency to spall or crack off; this point was later developed by Chapman (1964) as evidence of ablative heating.

C.V.Raman, who got the Nobel prize in physics, found (1950a) that Libyan Desert glass shows a kind of weak optical anisotropy, different from strain birefringence, and like that observed in plate glass. It seems to indicate flow during a semi-molten state.

The first study of oxygen isotope ratios in tektites was made by Baertschi (1950); he found that Java tektites show a deviation of +9.5 parts per thousand in the ratio of ^{18}O to ^{16}O , compared to Hawaiian sea water; moldavites and Darwin glass were also measured; and Silverman found similar values (1951).

Hammond (1950) calculated the rate of cooling of tektite glass from the strains left in the glass; he found that they cooled at a rate of about 50°C per minute, or more, especially between 700°C and 600°C .

Barnes (1951, 1961b) reported some light olive-brown tektites from the Muldoon area in Texas. He abandoned his earlier

ideas of a terrestrial origin of tektites, and suggested origin from sedimentary rocks on a destroyed planet. A similar idea was put forward by Cassidy (1956) and ~~W.A.~~ Ralph Stair (1956 a).

A crater at Aouelloul discovered by J. Galouédec was examined by ~~T.~~ Monod and ~~A.~~ Pourquie' (1951). They found a silica glass near it which obviously resembled Darwin glass. It was studied at the British Museum by ~~W.~~ Campbell-Smith (1951) and by Campbell-Smith and ~~M.N.~~ Hey (1952 a, b) who analyzed it and found it like Darwin glass in chemical composition. The crater appears to be an impact crater but the glass did not, at least at first sight, match the local sandstone in chemical composition.

H.E. Suess, son of F.E. Suess, measured the gas composition in tektite bubbles. He found a pressure less than 10^{-3} atmospheres. The composition was principally CO_2 and CO , with some H_2 and H_2O , but very little N_2 . For the age of the Australian tektites, Suess, ~~R.L.~~ Hayden, and ~~M.G.~~ Inghram (1951) found upper limits of a few tens of millions of years. ~~E.K.~~ Gerling and ~~M.L.~~ Yaschenko (1952) got similar results.

~~P.K.~~ Kuroda and ~~E.B.~~ Sandell (1954) confirmed Preuss (1935) in finding that molybdenum in tektites is low (0.5 ppm) compared with the figures for obsidian.

~~H.G.~~ Urey (1955, 1957, 1958a, b) argued that the distribution

bution of tektites over the earth could not have resulted from the fall of a shoal of bodies in interplanetary space, because the shoal would have been enlarged to the size of a meteor shower (enveloping the whole earth and more) by differential gravitational action of the sun. He thought that the distribution probably resulted, as Spencer had suggested, from a meteorite impact on the earth. Later (1957) he modified this to a cometary impact, since comets are probably less compact than meteorites, and might thus explain the lack of a crater correlated with e.g. the Australasian strewn field. Urey felt that it would be surprising if the moon could produce material whose composition is so much like that of a terrestrial clay.

~~Donald~~ Hubbard, ~~E. M.~~ Krumrine, and Stair (1956) applied the principles of glass technology to the tektite problem. They expected lumps of glass to break up ^{by thermal shock} during entry into the atmosphere, forming fragments of centimeter size. They noted that between 550 °C and 650 °C the expansion coefficient of tektites other than australites decreases (because of the approach to the transition temperature); they say that this means that the glass was quenched. They remarked that the striae which can be seen ^{in general} inside a tektite do not _{in general} turn, as they come to the surface, but end abruptly, as if the tektite had been broken from a larger mass. (Turning is observed on the front surface of australites; see P 11.)

They measured the spectral transmission characteristics, as did also ~~L.~~ Houziaux (1956).

¹⁹⁵⁵
Stair (~~1956~~) made the fundamental point that the production of a homogeneous glass, such as tektite glass, can not be done suddenly; time is required for the component oxides to mix. A collision (i.e. a meteorite or comet impact) does not give enough time.

~~G.H.R.~~ Von Koenigswald (1957) began a series of investigations of Java tektites, and ~~G.E.~~ Wilford (1957) reported tektites from Brunei, in the northern part of Borneo.

The years 1958 and 1959 opened a new period in the history of the tektite problem. ~~W.D.~~ Ehmann and ~~T.R.~~ Kohman (1958 a, b) reported (incorrectly, as it turned out) the detection of the radioactive isotope ^{26}Al in some tektites. This implied a long stay in space, and hence an extraterrestrial origin. The first international tektite conference was held in Washington. Baker's comprehensive monograph (1959^b) with its strong plea for the origin of australite sculpture by aerodynamic forces, was published. Nature published a series of short papers in favor of a lunar origin by ~~T.~~ Gold, ~~C.M.~~ Varsavsky, and me (1958), and against it by Urey, ~~Z.~~ Kopal, and ~~V.E.~~ Barnes (1958). The launching of artificial satellites by the USSR and the US increased interest in the tektite problem.

The period of the past 16 years is too close to be seen in historical perspective. It is therefore discussed, subject by subject, in Chapters 2 -- 10.

CONCLUSIONS

The study of tektites up to 1958 led to the following conclusions, which underlie modern work:

a. Tektites always occur as detached pieces, connected neither physically nor, with some doubtful exceptions, chemically with their surroundings

b. Tektites are not artificial glasses.

c. ~~Tektites are not the products of terrestrial volcanoes;~~
they are chemically more like terrestrial sedimentary rocks than like ~~terrestrial igneous rocks.~~

c. Although tektites resemble terrestrial volcanic glasses in their physical properties, they are not the products of terrestrial volcanoes; they are, in some chemical respects, more like sedimentary rocks.

CHAPTER 2

TEKTITE DISTRIBUTION: THE STREWN FIELDS AND THEIR GEOLOGIC RELATIONS

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The distribution of tektites over the surface of the earth is not random. In this they differ sharply from the usual meteorites, as can be seen from a comparison of Figs. 2-1 and 2-2. The clusterings of meteorites are only apparent, and are associated with areas of high industrial development. Thus meteorite discoveries, both falls and finds, are commonest in Europe and North America, while tektites are commonest in Southeast Asia and the Philippines. The meteorite finds are clearly controlled by the intensity with which the search for meteorites is conducted; on the other hand the distribution of known tektite finds is the revelation of a geographic pattern which is imposed by nature. Despite the intense geologic effort that has gone on for centuries in England and Germany, not a single tektite has been found in either country, yet a single cubic meter in the Philippines yielded over 100 (Chao 1964a).

In place of a random distribution of tektites, what is found is a distribution into what are called strewn fields. Each strewn field corresponds to a single event, which most workers would say was the fall of a large number of tektites^t. The neutral word strewn field^A was adopted at a time when a considerable number of workers considered that tektites might be produced in the localities where they were found, e.g. by volcanism, by artificial means, or by

THE STREWN FIELDS

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desiccation of a silica gel.

There are four (or possibly only three) generally recognized strewn fields, plus two (or possibly any number from zero to four) minor distributions of tektite-like material which may constitute strewn fields. The fields are shown on Fig. 2-1. The three major fields are the Australasian field, formed about -0.7 m.y., the Czechoslovakian field, formed about -15 m.y., and the North American field, formed about -35 m.y. The Ivory Coast strewn field, formed about -0.9 to -1.0 m.y., is regarded by Chapman as perhaps an extension of the Australasian strewn field; we shall here follow the usual practice of regarding it as distinct, but Chapman's doubts are to be kept in mind. Similarly we here regard the Australian tektites (australites) as part of the Australasian strewn field in spite of the serious and weighty objections brought forward by all Australian geologists who have actually examined the occurrences. The minor fields are the Darwin-Macedon glass field, formed about -0.7 m.y., which includes specimens found chiefly in Tasmania, but with a few pieces 500 kilometers away in Australia; the Aouelloul glass, formed at a date not firmly established, and found only near a small impact crater in Mauritania; and the Libyan Desert glass, found in the Sand Sea of Egypt. The Darwin glass is considered by many to be part of the Australasian strewn field; we shall here follow that idea, for reasons to be given below. The Aouelloul glass is very similar to the Darwin glass; it is not usually counted among the

tektites, but should probably be counted with them because it presents the same problems, particularly in the field of glass technology. Similarly the Libyan Desert glass is regarded by many students as a simple result of impact on the desert sand; but this view again encounters great difficulties from the point of view of glass technology and aerodynamics; hence it is logical to discuss this glass with the tektites.

THE AUSTRALASIAN STREWN FIELD

This enormous pattern (Fig. 2-3), covering about 1/10 of the total surface of the earth, has been discovered piece by piece. (For the separate portions, see Figs. 2-4, 2-5, 2-6, 2-7, 2-8.) For each portion of the strewn field a special name is employed. See Table 2-1.

Have we found the true limits of this field? Despite earlier suggestions by ^{T.W.E}David et al (1927) that all tektites result from the passage of a group of natural satellites of the earth over a single great-circle path, it is now clear that the dates of the moldavites and the North American tektites exclude them from the Australasian strewn field. Tektites have been sought in vain in New Zealand (Eiby, 1959); the boundary of the australite strewn field in Australia is very sharp (Fenner, 1940a); tektites have been mentioned but never brought in from New Guinea (von Koenigswald, 1960b); the alleged tektite from Timor proved to be an obsidian (Wichmann, 1882); the Sakado glass from Japan (Baker, 1959b) appears to be a terrestrial crystalline volcanic

rock with a film of glass; in Africa a number of specimens have been brought in as tektites and later identified as indochinites (Preuss, 1969, an unpublished study of a tektite reportedly from Nigeria) or as terrestrial igneous rocks (Saul and Cassidy, 1970).

Unity of the Australasian strewn field

Internally, there are strong reasons for regarding the Australasian strewn field as a unit. The external shapes (including the sculpture of pits, etc.) of the tektites form a continuous sequence, with blocky Muong-Nong type tektites in the north, decorated splash-form tektites in the center, and smooth flanged buttons in the south and east (von Koenigswald, 1967). (For the meaning of these terms, see Chapter 3.)

The Australasian strewn field consists of streaks of tektites of similar composition extending for thousands of miles, as was shown by Chapman (1971); see Fig. 2-9. Chapman finds essential identity in composition between tektites at points thousands of miles apart (e.g. West Australia and the Manila area, or Kuchenari, Thailand, and Port Bayard, South China). These streaks of constant composition tend to run perpendicular to the lines of constant morphology described by von Koenigswald (1967), as would be expected if the streaks represented the paths of groups of bodies and the morphology recorded some ballistic parameter, such as velocity, angle of entry, or the like. There is no correlation with the underlying rock (Fenner, 1940b).

The results of Chapman's are so remarkable that it is well to note that they are foreshadowed by Heide's finding (1936b, 1940b) that there is a central streak of nickel-rich tektites going from Indochina to Java, flanked on either side by streaks of low nickel content (Philippines to Australia, and Thailand); they are similarly foreshadowed by the finding of Schnetzler and Pinson (1963) that indochinites differ systematically from philippinites, especially in calcium content. Again, there is a note of S.R. Taylor (1964) on an isolated patch of high^h nickel australites which, in the light of Chapman's work, is seen as a part of one of his streaks. Again Tatlock (1965) noted some chemical correlations between tektites of Western Australia at Kalgoorlie and the tektites from the vicinity of Manila.

In support of the chemical studies, Chapman et al (1964) made plots of the density versus frequency, which he called population polygons of specific gravity. These plots showed the same relations ^{between} ~~to~~ regions that were found from the chemical composition. That is, regions with similar chemical composition also had similar population polygons of specific gravity. The orderly pattern showed by all these studies is strong evidence for the unity of the Australasian strewn field.

If the glass found at Macedon, Victoria, Australia (Baker and Gaskin, 1946) belongs with the Darwin glass, as appears from its composition (Chapman et al 1967a), then this may represent a streak

of high-silica glass very roughly parallel to the overall structure of the Australasian strewn field in this region. The Darwin glass itself is distributed along a narrow north-south streak in Tasmania; see Fig. ²⁻⁸~~2-5~~. Recently an apparent crater has been reported in this region, with abundant glass near it.

Another approach to the problem of the unity of this field comes from studies of the dating. Potassium-argon methods and fission-track methods (see Chapter 7), which measure the time since the last strong heating, give accordant dates of -600,000 to ⁸-700,000 years for all types of tektites in the strewn field, except the high-sodium tektites. For these a date of -3.7 m.y. is found by fission-track methods. The Darwin glass appears, on this basis also (Gentner et al, 1972), to be part of the strewn field.

Despite the above, Australian geologists are agreed that the australites arrived at the surface of the earth at a date near -14,000, rather than -700,000 (Fenner, 1938a, 1949, Baker, 1962b, Gill, 1965b, 1970a, Lovering et al, 1972). The papers of Gill and of Lovering et al supply clear evidence that tektites are found on top of recent Australian soils whose ages, as given by carbon dating, are less than 20,000. The evidence is strong that they did not reach this position by reworking from more ancient sediments at a higher level. The remarkable state of preservation of the fine markings on some of the australites indicates clearly that they have moved only

very small distances at most. For example, a Czechoslovakian study shows that stream erosion will reduce glass objects of roughly tektitic character to about 1/90 of the original mass at a distance of 40 kilometers downstream. Near Lake Torrens, Lovering et al (1972) found well-preserved tektites in a location where the nearest soils whose dates, on the accepted basis, would be -700,000 years were at a distance of 15 to 25 kilometers mountainwards.

Gill (1965b) surveyed a single square chain near Port Campbell, and excavated it carefully. He found 14 australites, all in the layer just above hardpan; the latter was dated by some carbonized stems at -5430 years. The layers with the australites were dated at -3750 or later.

Hodge-Smith (1939) remarks that on the gibber country (plains covered by wind-faceted pebbles) all stones show more or less uniform polish and weathering, except australites; some of them show no weathering while others have only traces of their original form.

One obvious solution to this puzzle can be ruled out. The tektites could not have floated around in space for a few hundred thousand years before falling to the earth; if they had, there would be clear chemical and physical evidence of attack by primary cosmic rays. This has been carefully sought for (see Chapter 7) and not found. Moreover the flanges of flanged australites, which appear to have formed during the descent through the atmosphere (Chapter 3), have

been dated by fission-track methods at -700,000 years, identical with that of the core (Storzer and Wagner, 1969).

Thus the age discrepancy remains as an interesting and significant puzzle. It appears that we must reject the very recent dates for the Australian tektites: something must be wrong, conceivably the dating of the hardpan. In this book I shall treat the australites as part of the Australasian strewn field; but it is to be kept in mind that the problem is not solved.

The relation of the microtektites to the larger tektites of the Australasian strewn field is regarded as doubtful by some workers, particularly in Australia (Baker, 1968^c). However, the demonstration by Frey et al (1970) that microtektites have the same trace elements as the larger tektites has given strong support to the supposed relation. The microtektites have been dated by ~~the~~ study of the magnetic behavior of the sediments in which they are found. The sediments record the reversals of the direction of the field. The microtektites are found at the Matuyama-Brunhes reversal (Glass and Heezen, 1967b) which has been dated by comparison with land lava flows at about -700,000 years. The date is the same throughout the field; note that microtektites have been found both north and south of Australia. The bottle-green microtektites are to be included in the strewnfield also, according to work of Glass (1972b) to be discussed further in Chapter 6. Similarly the chemical work of Barnes (1964c) shows that the Muong Nong materials, despite their different appearance

and internal structure, are chemically identical with the other indochinites and must be regarded as part of the strewn field.

THE IVORY COAST STREWN FIELD

In Fig. 2-10 is shown the Ivory Coast strewn field (Lacroix, 1934b, 1935a), together with the Bosumtwi crater in Ghana, from which many investigators think that these tektites are derived. Also shown are the locations of two oceanic cores in which Glass (1968, 1972b) found microtektites. The chemical compositions of the microtektites, particularly at the high-silica end, clearly relate them to the ordinary tektites of this strewn field. The total extent of the field is not well known; much of the land area is heavily wooded, and the tektites are not found at the surface but at depths of 5-6 meters in alluvial deposits. A careful guide to the strewn field was prepared by Saul (1964).

Only a few hundred Ivory Coast tektites are in scientific collections; all of these are splash-form tektites; neither Muong Nong tektites nor flanged buttons and related forms have been found among the Ivory Coast tektites.

It is important to see that the discovery of the microtektites means that the center of the known field is 700 kilometers from Bosumtwi, rather than 200, as earlier believed; and the field extends to a distance of 1600 kilometers from Bosumtwi. Moreover the angle subtended at Bosumtwi is about 45° ; thus one can no longer say that

the tektites are found on a line radiating from Bosumtwi.

According to standard fallout tables (Glasstone, 1962), a particle with a diameter of 200 micrometers is expected to fall to the ground in less than 2 hours. Since the microtektites include particles as large as 1 millimeter, it is clear that even very strong winds cannot have significantly altered the form of the strewn field.

THE MOLDAVITE STREWN FIELD

The moldavites cover two small patches in southern Czechoslovakia. (see Fig 2-11), one in the territory called Bohemia, the other in Moravia. The field has been described in detail by Vorob'yev (1964). The name comes from the German name Moldau for the Vltava River in Bohemia. The Czechs call these tektites vltavines.

Because of its occurrence in Central Europe, the moldavite strewn field has been extensively studied although the mass of glass involved in the ordinary tektites is only about 3000 tons (Bouška and Rost, 1968). Storzer and Gentner (1970) have interpreted some bentonite particles found in the Bavarian Molasse deposits ^(fossiliferous sediments) as micromoldavites chemically altered by contact with water. The data are still preliminary. About 200 kilometers from this field, in a direction south of west is the Ries Kessel, a large impact crater of late Miocene age which is regarded as the source of the moldavites by some investigators.

A valuable study of the process of destruction of glass during transportation by water was made by a group of Czechoslovakian students (Anonymous, 1971) who studied the rate of loss of weight for pieces of artificial glass in streams as a function of the distance downstream from the factory which made them. The students found that the glass lost about 99% of its mass in a distance of 40 kilometers. This study suggests that the moldavites can not have been moved very great distances -- probably not more than 10 kilometers. Bouška et al (1968) reach similar conclusions. It follows that the moldavites must have fallen near the locations in which they are found.

The Bohemian moldavites are slightly different in chemical composition from the Moravian moldavites. Each of the two small strewn fields is elliptical, with the major axis in the NW-SE direction. In each of the subfields, there is a distinct gradation in size, so that the specimens from the NW end of the subfield average about 3 times as heavy as those from the SE end (Simon, 1963, Bouška et al, 1968). These differences are much larger than the differences in average weight between the two subfields. Qualitatively, the subfields are like the fields produced by meteorite falls (Nininger, 1952), although the gradient in size is not as steep as in meteorites, and the field is relatively long. If this is the explanation then the moldavites entered the atmosphere at an angle over 90° to the direction from the Ries crater. Bouška et al (1973) note this possibility. They seek, however, to explain it on the ground that the moldavites

have been reduced in size by stream erosion. Their explanation seems somewhat artificial since the Vltava (in Bohemia) flows north, while the Jihlava (in Moravia) flows southeast, but the heavier tektites are at the NW in both fields.

The geologic age of the strata in which they are found is late Miocene. Janoschek (1936) stated that near Dukovany he had found layers of tektite-bearing gravel interfingering with marine deposits which had fossils of Oncophora; these would give a date of late Helvetian. Bouška (1964) revisited the site, and found that the moldavite-bearing gravels overlie the Oncophora layers. Zebera (1968) studied some ancient lake bottoms, where he found occasional pairs of tektites, consisting of fragments of a single original piece, the two fragments being only a hundred meters or so apart. These, he feels, cannot have resulted from redeposition, which would have separated the fragments much further; and hence these deposits are where the tektites first fell. They are found in Vrabce clays, above the Mydlovary formation, which is of lower Tortonian age. The Tortonian is Upper Miocene, and just above the Helvetian. The catastrophe which formed the Ries is also of Tortonian age (Preuss, 1964) and hence cannot at present be distinguished in time from the moldavites.

Potassium-argon ages for the moldavites and the Ries also agree (Gentner et al, 1963; see Chapter 7). Thus the geographic data point away from the Ries as the source of the moldavites, while the chronological data point toward the Ries.

THE NORTH AMERICAN STREWN FIELD

The core of our knowledge of the North American strewn field comes from the bediasites (see Fig. 2-12), found in Texas in a narrow strip of land paralleling the Gulf Coast, and about 150 kilometers inland. The bediasites are found close to the outcrop of the Jackson formation, which ^{is} uppermost Eocene. Tektites from the southern part of the bediasite area, near Muldoon, are often lighter in color (Barnes, 1951). Chao (1963b) notes that they are associated with a lag gravel characterized by a reddish chert.

Tektites of related age and composition in Georgia were first reported by Bruce (1959), chiefly in Dodge County; one was also found in Washington County (Pickering and Allen, 1968). A large number were found by Howard (1968). They are found, as King notes (1962a), in a surface gravel overlying the Hawthorne mottled clays. The difficulties in explaining this problem are noted by Furcron (1961). King attributes the gravel to a "Pleistocene-Pliocene wash" covering the whole area. In fact, the tektites are typically found, not on stream terraces, but on the divides. Personal examination convinced me that the gravel is a lag gravel; one sees everywhere pebbles on the top of small earth pillars (demoiselles) of Hawthorne clay. In the ditches one can see how the gravel is being produced by the washing of the clay. The sharp contact noted by King (1962a) is an isolated example of a stream deposit; at most tektite sites the contact between the gravel and the clay is gradational and is only a decimeter or so

below the surface. The Georgia tektites^t seemed to me to be weathering out of the Hawthorne. Most of those in Dodge County seem to come from points between the 300 and the 325 foot contour on the 1:250,000 map.

The Hawthorne is generally assigned to the Miocene; but it shows no fossils within about 100 kilometers of Dodge County. In this county it overlies a limestone which is called Oligocene. However, the well logs, which have been studied and compiled by Herrick (1961) systematically note the presence of Middle Eocene foraminifera in this limestone. Although the well logs note the possibility that these foraminifera may have been reworked, Herrick (personal conversation, 1973) remarks that they do not appear reworked. It is thus not inconceivable that the lower Hawthorne is of late Eocene age, or Oligocene.

The single Massachusetts specimen is from ~~from~~ Gay Head, on Martha's Vineyard (Kaye et al, 1961). It was found in a gully, clearly displaced. It was 8 meters below the top of sands dated as Raritan (early Late Cretaceous). Above them is the Aquinnah conglomerate, itself a reworking of Cretaceous and Miocene deposits; above that is Middle Pleistocene and Holocene sand.

Microtektites apparently related to the North American strewn field have been reported by Donnelly and Chao (1972) and Glass et al (1972). The cores are in the Caribbean, near the island of Curacao. In addition, there is a single tektite from Cuba (Garlick et al, 1971) which seems to be compositionally related to the North American strewn field. It

was doubted at first; but the same chemical peculiarities which raised the doubts appear in the microtektites along with compositions whose relation to the bediasites is close. The date of the microtektites is again late Eocene, as judged from the stratigraphic data in the cores.

From the geological standpoint it is interesting to ask whether the North American strewn field can be reliably placed in the late Eocene, since the K/Ar and fission-track ages are about 35 million years at most, whereas Kulp (1961) places the top of the Eocene at -36 million years.

THE THREE MINOR FIELDS

Libyan Desert glass

Clayton and Spencer (1934), acting on reports from the Survey of Egypt, visited this difficult location ^(Fig. 2-13) and collected about 50 kilograms of this glass. Spencer (1939) returned to the area and estimated that the field extends from $25^{\circ}2' N$ to $26^{\circ}13' N$, and from $25^{\circ}24' E$ to $25^{\circ}55' E$, an area 130 km north and south by 53 km east and west. Isolated pieces, at least some certainly transported, were found at distances of some hundreds of kilometers. The material probably exceeds the moldavite strewn field both in quantity and in area. The age is 28.5 million years, by fission-track dating (Gentner et al, 1970^a). Its relation to other tektites is open to some question, because it is nearly pure SiO_2 . The reasons for grouping it with the tektites are discussed in later chapters; the

principal reason is just the difficulty of explaining how large chunks (up to 7 kg) of this very viscous glass could be produced and freed of volatiles by natural processes on the earth.

The material is found between dunes on the flat desert floor in a reddish soil containing much calcium and magnesium carbonate, gypsum, ferric oxide, and clayey materials. This soil overlies the so-called Nubian sandstone { according to Pomeyrol (1968) the term is so widely applied (Libya to Sinai, Cretaceous to Tertiary) as to be meaningless}. The dunes, which are very sharply set off from the desert floor, consist of yellow sand. On their tops are found fulgurites (glass tubes formed by lightning), which are entirely different in structure from the Libyan Desert glass, being thin-walled and full of bubbles.

A crater exists in the vicinity, at $22^{\circ} 20' N$ and $25^{\circ} 30' E$. Meteorites were sought in the area of the Libyan Desert glass by Spencer, without success. The crater and the strewn field were revisited recently by Barnes; the results are not yet published.

Aouelloul Crater glass

A small quantity of glass, resembling Darwin glass, is found in the immediate vicinity of the 250-meter crater of Aouelloul, in the Mauritanian Adrar (Sahara) at $20^{\circ} 15' N$, $12^{\circ} 41' W$, in level sandstone of early Ordovician age, far from any volcanic site. The crater is generally regarded as an impact crater (Campbell-Smith and Hey, 1952a, b).

The question has been raised by Campbell-Smith and Hey whether we are to regard the crater as excavated by a block of glass, or to regard the glass as formed by meteorite impact on the local (Zli) sandstone. It is classed with the tektites because of its similarity to Darwin glass, and because of the difficulties of glass formation in the very brief moments of a meteorite impact.

The glass is found around the crater, especially on the east side. It extends at least a kilometer eastward; extensions in other directions have not been noted.

The K-Ar age is 18.6 m.y. (Gentner et al, 1968); the fission-track age is about 0.3 m.y. (Fleischer et al, 1965b). The freshness of the crater suggests that it was formed at ~0.3 m.y.; the higher K-Ar age would then mean that argon was preserved through the crater-forming event. The fission-track age may also be too low; Cressy et al (1972) refer to a determination of 3.5 m.y. by Storzer, who corrected for track fading.

The Ordovician locally comprises two layers, O₂ (Oujeft sandstone) and O₃, the next higher layer (Zli sandstone). The O₃ is distinguished from the O₂ by the presence of vertical fossil burrows (tigillites) (Monod and Pourquie, 1951).

Amerikanites

There is a class of glass bodies, often spheroidal in shape, having markings resembling those on splash-form tektites, found in

Peru, Ecuador, and Colombia (Stutzer, 1926, Codazzi, 1929, Martin and deSitter-Koomans, 1956) which are called mucusanites or amerikanites. They are connected by chemical composition with local lava flows; in some cases they seem to represent sediments which have been melted and then erupted. They are not accepted generally as tektites; however, if it should turn out that tektites are the product of lunar volcanoes, it is possible that the amerikanites are analogous terrestrial objects.

CONCLUSIONS

The details of the tektite strewn fields are full of clues to the origin of tektites. Without entering on these questions, it may be helpful to the reader at this point to list a few points which seem to be clearly implied by the geography of the three largest strewn fields, namely the Australasian, Ivory Coast, and North American strewn fields:

a. These tektites are not local products; in each field the tektites occur on top of a wide variety of sediments or igneous rocks, with no traceable connection.

b. These tektites probably arrived at their present locations by ballistic flight through space, whether from an earthly or a cosmic source; no reasonable method of distribution within the earth's atmosphere has been suggested.

THE STREWN FIELDS

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c. In Table 2-2 below is shown, for the three largest strewn fields, the radius of the minimum circle which will cover the field, and the velocity needed to cover the field in case of terrestrial impact, starting from the center of the circle.

THE SHAPES OF TEKTITES

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INTRODUCTION

In this chapter we shall study the shapes of tektites, beginning with those whose form is best understood, and working back toward earlier and more primitive forms.

Definitions

Tektites occur in four general classes of forms:

Microtektites, Pl. 8, usually less than 1 mm in diameter, and found, so far, only in ocean-bottom cores, but clearly associated, both in composition and geographic location, with other tektites.

Muong-Nong type tektites, Pl. 9, 10, blocky in shape and layered in structure.

Splash-form tektites, Pl. 11, 12, 13. These form the great majority of all known tektites. They look like congealed drops of some viscous liquid; they are shaped like spheres, drops, dumbbells, hamburgers, etc. They are typically decorated with corrosion markings of various kinds: cupules, (hemispheric pits of sizes up to about 1 mm), Pl. 14; gouges (elongated depressions, with sharp edges, U-shaped in cross section, and with a length which is several times ~~the~~ ^{the} width), Pl. 15; meandrine grooves (U-shaped in cross-section, and in plan like worm tracks in old wood), Pl. 16, 17. Sometimes, especially in tektites from Anda (Pl. 18), in the Philippines, the grooves show an astounding appearance of multiplicity, as if they had been dug out by the claw of an animal.

Flanged buttons, Pl. 19, and related forms; these are found principally in

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Australia. The central part, or core, is typically lens-shaped. On one side there are often concentric rings, spaced a few millimeters apart, called ringwaves; these may also take the form of a double spiral.

The side with the ring waves is called the anterior side; it was almost certainly in front while the tektite was coming down through the atmosphere. The opposite, or posterior, side often has indications of corrosion, though usually not as strong as on the splash-form tektites. Around the edge there is, in some well-preserved specimens, a flange formed by glass dragged off the anterior surface presumably by the air stream.

The splash-form tektites and the flanged buttons, when sectioned, show a system of irregularly wandering striae (Pl. 20), in the interior, of varying color, hardness and composition.

Many tektites have been subjected to a process of spallation, i.e., the breaking-off of a more or less flattened piece from the outside, apparently as a result of thermal shock. Occasionally, the spallation is incomplete: a portion of the spalled surface adheres, so that it is possible to be sure that this is how the remainder of the surface was lost (Chapman, 1964).

THE FLANGED BUTTONS AND RELATED FORMS

Observations

The best-understood shapes among the tektites are the forms of the flanged buttons (Pl. 19). Flanged tektites are almost unknown outside Australia; and the well-formed flanged buttons

occur chiefly in southeastern Australia.

The understanding of these forms was developed in the papers of Stelzner (1893a,b), Fenner (1934, 1935, 1938a, 1940a, 1949), and Baker (1940, 1943, 1944, 1955b, 1958a,b, 1959a,b, 1960a,b, 1963d, 1967b). The evolutionary sequence as finally worked out by Baker is indicated in Fig. 3-1. The tektite enters the atmosphere as a relatively smooth glass ball. Glass is first lost from the anterior surface; of this glass, the portion in the equatorial zone is lost, at least in part, by spalling. When half or more of the central diameter has been lost, it seems to become possible for glass to accumulate on the lee side of the tektite, to form the flanged button. CR.

Experiment

Chapman et al (1962) made some experimental studies in wind tunnels which showed that in fact an airstream is capable of producing the observed effects on tektite glass. Since the Mach 15 to 25 velocity of a tektite with respect to the air cannot be simulated in a wind tunnel, resort was had, as usual, to an arc jet, in which the air is strongly heated by an electric arc, and is then driven toward the model at about Mach 3. The total energy content of the stream (internal energy plus kinetic and mechanical energy) is the same as

that in the actual case; and the fact that the velocity is different does not matter because behind the shock the air velocities are always subsonic in any case.

Pl 21

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Chapman's remarkable australite-like models (see Plate 6, upper line) were not produced starting from spherical bodies; instead, his models in these cases started from lens-shaped pieces of tektite glass. Hawkins (1963), working with AVCO windtunnels, attempted to produce the flanges experimentally by starting with spheres; he was not successful. In his experiments the melt flow went around to the back of the sphere; the results seem to have resembled some javanites described by von Koenigswald (1963b) in which an outer layer, apparently of melt glass, forms festoons on the posterior surface. Among the australites these objects are called crinkly tops by Fenner. It is known from Fenner's studies (1938a) that flanges are not found attached to tektites until the main body of the tektite has been reduced to a lenticular form; in addition, Hawkins gives aerodynamic reasons for expecting that in his wind tunnel the flange glass will be lost, while in Chapman's somewhat faster airstream, it will stay on.

Calculations

It is possible to calculate the ablation phenomena, using a theory developed for heat shields of artificial satellites and missiles. The plan of the calculations is to account in detail for the heat dissipated as the tektite moved through the air. A mass m of air encountered by the tektite moving at a velocity V as seen by the tektite, contains an energy $1/2 mV^2$, plus relatively unimportant quantities of energy which it contains as a result of the initial temperature. Of this energy, a calculable fraction is dissipated at the shock; this is radiated away. Back of the shock is a layer of air a millimeter or so deep, called the gas cap. In contrast to the ambient atmosphere, which is cold, thin, and moving at hypersonic speed past the tektite, the gas cap consists of hot, dense air, which moves relatively sluggishly, at subsonic speed, over the tektite surface. Most of the energy of the airstream has been converted at the shock from kinetic energy of motion to thermal energy. As the gas cap flows over the tektite surface, it carries away with it most of the energy of the airstream, which then disappears into the wake.

The gas cap is at a temperature on the order of 7000°K . Between it and the tektite surface there is a very thin layer of air, the boundary layer, whose base is at the temperature of the tektite surface, and whose top is at the temperature of the gas cap. It is

through this layer that most of the heat comes which the tektite must cope with. This heat is denoted q_{aero} . A small amount of q_{aero} is radiated back into the air; another small amount is absorbed in heating the body of the tektite. But most of the heat goes into melting and vaporizing a thin layer of glass a tenth of a millimeter thick or less. The critical question concerns the balance between melting and vaporization.

If the layer is thick, then the forces of skin drag will pull it away from the stagnation point; it accumulates in the lee of the tektite edge, as the flange.

If the layer is thin, then viscous forces, which depend on velocity gradients, are able to hold the liquid in place until the heat supplied is enough to vaporize it. In the first case, about 500-600 kcal/kg are consumed; in the second case, around 3000 kcal/kg are used up.

A first attempt at a calculation of the flow was made by O'Keefe (1960); this was immediately superseded by the work of Chapman (1960). Adams and Huffaker (1962a, 1964) and Chapman and Larson (1963) produced detailed mathematical programs which gave the calculated ablation as a function of entry angle and entry velocity. Of these calculations, those of Chapman and Larson indicated that most of the ablation in tektites always occurs as the result of melt flow; in their calculations, this always predominates over vaporization by a large factor. For 1 cm tektites entering at 11 km sec⁻¹,

the ablation ranges from 8 mm to 15 mm, depending on the entry angle, and being largest for the shallowest angles of entry. The calculations of Adams and Huffaker (1964), on the other hand, were based on a vapor pressure for tektites which was much greater than that accepted by Chapman and Larson. Adams and Huffaker found large ablation and melt flow only for angles which nearly graze the upper atmosphere (skipping trajectories, in particular, which actually climb out of the atmosphere and then fall back) ; moreover, they found that vaporization can remove as much as 60% of the tektite. Their use of a high vapor pressure was attacked by Centolanzi and Chapman (1966) who demonstrated that the vapor pressures of Walter and Carron (1964) (which were used by Adams and Huffaker) referred to the most volatile constituents of the tektite only (for example, water); and that the vapor pressure corresponding to the majority of the matter of the tektite was not far from that of pure silica, as Chapman and Larson had assumed. The accuracy of the calculations of Chapman and Larson was confirmed by O'Keefe et al (1973) using the theories of Adams and of Warmbrod (1966). (See Fig. 3-2).

The vitally important fact, on which all these calculations agree, is that the amount of ablation observed on australites corresponds to velocities coming from space (i.e. on the order of 11 km/sec). It is much too great for the kind of velocities to be expected for tektites which are following ballistic trajectories from one point to another on the earth (see Table 2-2); these range up to about 6 km/sec. As we shall see, it is possible to understand how tektites moving at 11 km/sec might suffer much less ablation than that of Fig.3-2; what is not comprehensible is how tektites moving at 6 km/sec or less could suffer as much ablation.

SPLASH-FORM TEKTITES: THE CORROSION PROBLEM

Thus a difficulty has arisen in understanding tektite ablation. The aerodynamic calculations indicate that nearly all ablation is by melt flow, and ablation is always a matter of the order of a centimeter, and hence sufficient to change the overall shape of a tektite of typical size in a significant way. In fact, however, splash-form tektites almost never show evidence of melt flow; the only exceptions are some javanites (von Koenigswald, 1963b, see Plate 00). Moreover, the shapes of a large class of tektites are those of liquid drops: spheres, dumbbells, etc., without the changes of overall shape which is observed in australites and is predicted by the theories of Chapman and his coworkers. Chapman explains the absence of evidence of melt flow by saying that the

Pl.22?

outer surface, with the marks of aerodynamic ablation on it, has been removed by spallation, followed by etching by ground chemicals. There is no doubt that spallation does account for important features, particularly in the sequence from australites to Philippine tektites (Plate 23). The meandrine grooves seen on the lower (anterior) side of these tektites are probably an indication that thermal shock has taken place; hence spallation is plausible.

In general, however, the question of the amount of corrosion by ground chemicals is a critical point in understanding the aerodynamic effects on tektites. The abundant evidence on this point is widely scattered through the literature; it will be summarized in the next section.

Causes of tektite corrosion

Let us adopt the term corrosion (Suess, 1900, p. 256) for the process by which many tektites acquired their characteristic sculpture of grooves, pits, notches and gouges. In using this term we do not intend to imply anything about the origin of the corrosion, whether aerodynamic or chemical or from any other cause.

Corrosion on australites

A typical australite button has three different kinds of surfaces: the anterior, surface, the rear surface of the flange, and the true posterior surface (seen bulging upward within the ring of the flange.). It will be shown that chemical attack has been negligible in shaping each of these surfaces.

Clearly there has been little attack on the anterior surfaces of the flanged buttons. Corrosion is normally not shown at all; occasionally there are a few small hemispherical pits. The maximum amount of loss by ground chemicals can be estimated from the curvature of some striae which are observable in the glass. The striae are due to variations in the composition of the glass; they form a complex system of thin folded structures inside the tektite, like a crumpled wad of paper. As the striae approach the anterior surface, they turn aside and run parallel to it; this is an obvious

(Pl 20)

result of the flow of the glass, under the influence of aerodynamic drag, away from the center of the anterior surface and around toward the sides and back. By fitting theoretical curves to the observed striae, Chapman et al (1962, p.14) have estimated that only about 0.12 mm were removed after the tektites stopped ablating.

Like the anterior surfaces, the posterior surfaces of the flanges show very little evidence of corrosion. Study of the flanges has not been made in the same way as on the anterior surface, but it is reasonably clear from photographs of sections of flange glass that there has been little chemical loss.

C.R.?

On the posterior surface of the main body of the australite - which is usually referred to as the posterior surface -- there is often corrosion, particularly in the form of small hemispherical pits, and it often happens that the striae are seen standing out in relief. McColl (1966) notes that this resembles the corrosion seen in other tektites. It is important to decide whether this corrosion is due to ground chemicals or was already present when the tektite fell.

The difference between the anterior and the posterior surfaces of the australites cannot be somehow a result of their position in the ground (e. g. the lower surface being differently attacked from the upper surface) because the flange glass shows no corrosion in many

cases when the posterior surface of the main body is corroded.

It is reasonably certain that at least some of the corrosion on the posterior surface is produced before the tektite strikes the ground, because it has been found under the flange glass. Dunn (1912a) illustrates this point by photographs of flanged australites which have been sliced perpendicular to the axis of symmetry, right through the region where the flange joins the core. Baker (1944) noted pits under the flanges, sometimes infilled with flange glass. Barnes (1962b) also noted hemispheric pits, which he attributed to bubbles, filled with flange glass. Baker (1963a) concluded that the sculpture of the posterior surface is pre-atmospheric.

On the other hand, it is clear from other thin sections made in the same way that the posterior surface of the australite is sometimes much rougher outside the flange than under it. This roughness is on a scale of a few tenths of a millimeter; and it follows the ~~schlieren~~ ^{striae}. Clearly this attack occurred after the tektite reached the earth. Clearly, also, it is entirely different from the sculpture of the splash-form tektites, since it follows the ~~schlieren~~ ^{striae}, while the typical sculpture of splash-form tektites does not.

The lack of attack by ground chemicals on Australian tektites would of itself suggest that attack by ground chemicals is very slow, except for the unfortunate fact that, as mentioned in Chapter 2, the date of arrival on earth of the Australian tektites, which include almost all of the flanged tektites, is controversial. In that chapter, however, strong arguments were put forward indicating that the australites belong to the Australasian strewn field. It follows that the absence of terrestrial etching on australites (more exactly, the very low level of etching) is evidence that the rate of attack has been small. This evidence is significant not only for the very arid areas

of Australia, but even for the more humid areas; Baker (1960b) goes so far as to say that the best-preserved australites are from humid areas.

Corrosion on splash-form tektites

Von Koenigswald (1963a) points out that flight markings, melt flow and flanges also occur on some javanites ^(PL 22) (though no flanged buttons); in this case the tektites are found associated with mid-Pleistocene fauna (von Koenigswald, 1958): Homo erectus and a primitive elephant-like animal Stegodon. The presence of the melt flow suggests that the Australian tektites are only an extreme case of general trends across the Australasian strewn field, and hence should have the same age as the others; these are dated both by K-Ar and fission track, and also by ^Sstandard geological methods, at -700,000 years.

The evidence for melt flow consists of rolled-up flanges, like those on australites, flow ridges, like the concentric flow ridges of australites, and in many cases an anterior surface whose curvature is markedly less than that of the tektite as a whole. The ablated surfaces are free of corrosion; yet in general the javanites belong to the family of splash-form tektites and are corroded (von Koenigswald, 1964).

Among the javanites, von Koenigswald (1961b) has drawn attention to a particular hollow specimen which appears to have been plastic when a pit was inflicted on it. The tektite was afterward broken open by natural causes, and it ^{is} possible to see the inside of the tektite; there is a lump on the inside just back of the pit on the outside, as if the pit had resulted from some inward-acting force while the tektite was still plastic.

Beyond Java and Indonesia, in the South China Sea, between the Philippines and Indochina, four tektites were brought up by a dredge haul from the bottom of the sea (Saurin and Millies-Lacroix, 1961) whose exterior sculpture differed little from that of land tektites. These were examined by Barnes (1971a) who found attached nannofossils which could be dated at -1.0 to -1.3 million years. Since the sculpturing must have been complete before the nannofossils were attached, Barnes concluded that the rate of attack must have been much more rapid in the earlier part of the life of these tektites on earth. The evidence is obviously more easily explained ^{as a result of} by sculpturing before arrival at the earth.

If in fact the sea tektites were etched by sea water, then it is difficult to understand the existence of the microtektites. There are many of these in the size range around 40 micrometers. Since the

total amount of corrosion is typically on the order of 1 or 2 millimeters, it is clear that if this corrosion had persisted for a time only 2% greater, all of the smaller microtektites would have disappeared completely. It is also difficult to understand why tektites whose initial radius was, let us say, 1.02 millimeters should have been so much more abundant than those whose initial radius was 1.05 millimeters; yet if etching had removed 1 millimeter, the first set would have become the present 40 micrometer spheres, and the second the present 100 micrometer spheres, which are much less abundant. It is much more likely that the etching has been essentially zero in the sea, and therefore that the sea tektites were already corroded when they arrived. This conclusion is strengthened by the recent discovery (Glass et al, 1972) of microtektites in the Caribbean, which have survived for 35 million years under the sea, or about 50 times longer than the Australasian microtektites.

A large number of tektites have been found on the Indonesian island of Billiton, in the course of tin mining operations. These were examined by Easton (1921) who pointed out that while many of them have the forms of complete droplets (spheres, pears, etc.) there are also many forms which appear to have broken. He found that the typical tektite sculpture never appears on the broken surfaces. This

could be understood only if the break occurred after the period of sculpturing. Yet the broken surface was not truly fresh, as it would be if the miners themselves had broken it.

The absence or scarcity of sculpture on broken surfaces was also noted by Suess (1900, pp. 257-258) on moldavites; by van der Veen (1923) on billitonites; by Lacroix (1929a, 1932) on indochinites; by von Koenigswald (1961b) on javanites (as well as billitonites); by Barnes (1939, p. 503) on North American tektites; by Rost (1969) and Zebera (1968) again for moldavites. Rost notes that when two fragments of the same tektite are found separately and are reunited, it can be seen that the common surface is only slightly etched. Kaspar (1938) notes that when moldavites are broken, exposing the interior of an ancient bubble, the bubble surface is never corroded. Lacroix (1930) notes the same for indochinites (Pl. 6, 7); it is shown on a thailandite (Pl. 24, 25, 26) and on a lei-gong-mo (Pl. 27, 28). It is incredible that in every case the tektite could have been broken only a short time before it was found.

New paragraph

The evidence on the moldavites is particularly interesting; some of these have obviously been worn by stream erosion. Zebera (1968) notes that even when the stream action can be dated, and took place millions of years ago (Pliocene), there is no sculpture formed on the worn surfaces. Baker (1937) noted that in a collection of 83 tektite fragments only 2 could be put together; he concluded that fragmentation took place in flight.

Nininger and Huss (1967) found two indochinites (Fig. 1) which appeared to have suffered incomplete breaks while still in a plastic condition. The surfaces of these tektites are covered with the usual decorations, except where the plastic break exposed new surfaces. There is a clear implication that these tektites broke while still in a plastic condition, but after the completion of the sculpturing. Since the tektites could scarcely have been made plastic after they reached the ground, this appears to be evidence that these tektites at least were already corroded when they struck the ground.

Suess (1900) made a fundamental contribution to this problem in a monograph on the Czechoslovakian moldavites. He found that the markings on the moldavites are arranged in patterns which depend on the overall shape of the tektite. This result is understandable if the patterns are produced by vortices and shock waves in hot gases, since these must satisfy differential equations of fluid flow which involve the shape of the specimen. The result does not make sense if the patterns were produced by the blind action of underground chemicals or plant roots.

For example, Suess found that if the tektite has the general shape of an oblate spheroid (like a Gouda cheese) then a system of gouges is often found, which radiate from the center of one face. Pl 31, 32

On very flattened spheroids (watch-shaped bodies) there is often a set of gouges which go across the rim in a direction perpendicular to the equator of the body. On convex surfaces, the gouges tend to run in the direction of greatest curvature, while on concave surfaces the gouges run in the direction of least curvature. A hemispherical pit is often found to be the center of a star-like configuration of radial gouges. When a surface contains mostly hemispherical pits, the gouges are not seen (Pl. 14). When a surface has pits on one part, and gouges on another, the regime of pits appears to precede the regime of the gouges.

Somewhat similar rules were found to hold for billitonites by Easton (1921); navel-like depressions occur on the most strongly-curved surfaces, for example.

Suess also found that the sculpture of moldavites is not usually related to variations in chemical composition. The surfaces of tektites generally show some faint swirling marks (Pl. 33, 34) which look like what you would see if you cut through a crumpled and folded stack of pancakes. These lines are called the streaky structure. The streaks are related to the chemical composition of the tektite; streaks with more silica tend to stand out very slightly. They correspond to the striae (Pl. 20); they are the lines where the striae come to the surface. The important point is now that the streaky structure may run at any angle to the gouges of the main tektite structure. In a detailed piece by piece description of some 43 specimens, Suess (1900) makes this point again and again.

If, on the other hand, a tektite is put into a weak solution of hydrofluoric acid, so that it is slowly etched away, then Suess found that this artificial attack follows the lines of the streaky structure. One would therefore expect that if the sculpture is due to ground acid etching, it would also follow the lines of the streaky structure; but the major sculpture does not.

When tektites have been found chipped by primitive man, it is always found that the chipped surfaces are uncorroded. ~~For moldavites~~ For the moldavites found at Willendorf (Pl. I) this is noted by Suess(1914). Beyer (1934b, p. 106) reports the same for late Paleolithic artifacts made from Philippine tektites. (Pl 2, 3)
Baker (1962b) finds a similar result for Australian chipped tektites.

When glass is attacked by ground chemicals, a residue of highly silicic material is left behind (Rzehak, 1912b, Brill, 1961). This residue has been observed on obsidians (Wright, 1915); it is in fact used for purposes of dating. Baker((1961e) found that etching with citric acid, a normal soil constituent, produced a white crust. It is not produced by hydrofluoric acid. But no such residue has ever been noted on a tektite when found.

In favor of the origin of tektite sculpturing by ground chemical activity is the fact noted by Berwerth (1910) to the effect that tektite sculpture is not really like the sculpture of meteorites; and that on meteorites the effect of atmospheric ablation tends to round the

bodies, rather than to roughen them. Linck(1928) used similar arguments. Diaconis and Johnson (1964) attempted to produce the typical tektite sculpture by using artificially heated tektites, since this can tend to make the boundary layer turbulent. Once again, it turned out that the effect of aerodynamic ablation, when entry into the earth's atmosphere is simulated, is to smooth the specimens rather than to produce the characteristic tektite sculpture. Only when air of much higher density was used did the sculpture appear (Golden and Blackledge, 1968). This result can be understood if the sculpture is not atmospheric but is due to envelopment in some gas such as that which launched the tektite. Linck(1928) suggested that the tektites had been launched from a lunar volcano, and that the sculpture was the mark of these volcanic gases. For the moment, the point to see is that this objection, namely that the earth's atmosphere will not do the trick, does not necessarily imply that the sculpturing is produced by ground chemicals.

Van der Veen (1923) removed all of the existing sculpture from some tektites, then heated them and quenched them in a water jet. He found that a set of cracks developed on the outer surface. If the tektite is then attacked by HF, the attack follows the pattern of the cracks, and the resulting pattern of grooves is very much like the meandrine grooves seen especially on some billitonites. Like the

(Pl 16, 17)

natural grooves, the grooves so produced were found to have a U-shaped cross section. These results were confirmed by Centolanzi and Chapman in some unpublished work which they kindly communicated to me (1973). In this case, the resemblance to tektite sculpture is really convincing. It seems possible that some kind of attack really can occur along such cracks. A possibility that does not seem to have been excluded is that during the formation of the crack itself, powerful local stresses produced a mesh of small cracks around the main crack. Later the chips fell out, or were dissolved out by some very short-range action. A similar explanation might apply to the deepening of the crack between the flange and the core, which can be seen on some australites; the flange glass is at a different temperature from the core glass when they are welded together. Glass has found that when two microtektites are welded together, a groove is found along the line of contact. In this case, however, the groove is found to be V-shaped in cross-section.

Baker (1963d) considers that the sculpturing must be due to ground chemicals because he feels that the Australian flanged buttons are very young. The buttons are clearly not corroded on the anterior surfaces, and he feels that these two facts are connected. This argument evidently falls to the ground if australites have the same

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age as the other Australasian tektites. Curiously, Baker regards the sculpture of the posterior surfaces of flanged australites as preterrestrial. He notes (1963b) the mixture of corroded and uncorroded tektites side by side in Western Australia at Nurrabiel. He finds (1961e) that acid attack is closely related to the striae (which is not usually true of the corrosion).

Summary

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Summing up, the arguments in favor of the terrestrial origin of the tektite sculpture are:

a. The absence of sculpture on australites, especially the anterior surfaces, combined with carbon-14 evidence for the low ages of the australites.

b. The demonstrated relation of the meandrine grooves to cracking, particularly thermal spalling.

c. The failure of experiments to produce sculpture by aerodynamic processes which simulate atmospheric entry.

Against the terrestrial origin of this sculpture are:

a. Evidence that the australite flanged buttons have been on earth as long as other Australasian tektites; this evidence comes (for the microtektites) from fission tracks, K-Ar dating, paleomagnetism, and the close chemical ties of australite groups to other Australasian tektite families. If the high age is accepted, then the lack of pits and gouges on the anterior surfaces of australite flanged buttons and the evidence for low (0.12 mm) loss of surface glass becomes evidence pointing against the terrestrial origin of the tektite sculpture.

b. Sculpturing, especially pits, on the posterior surface of australites, especially that under the flange glass, which is qualitatively similar to the sculpture on the splash-form tektites.

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c. Pits and other sculpture on some surfaces of javanites, with australite-like ring-waves on other parts of the same tektites.

Flanges on tektites directly associated with Pleistocene fossils.

d. Existence of microtektites, many less than 40 micrometers in diameter, for periods up to 35 million years in sea water. Some Australasian tektites with sculpture ^{are} found in waters which also have microtektites 700,000 years old.

e. Absence of sculpture on broken surfaces, on the interior of broken bubbles, and on surfaces formed by plastic breaks.

f. Correlation of pits and gouges with overall shape; lack of correlation with compositional variations.

g. Lack of the siliceous crust usually formed by glass decomposition.

The arguments against the terrestrial origin of the sculpture appear overwhelming. The arguments for terrestrial origin can be met if:

a. The australites have the same age as other Australasian tektites.

b. The meandrine grooves are due to thermal cracks enlarged by some mechanism other than chemical attack. Note that the Bikol ^(Cebu Group) tektites ^(PC) (Beyer, 1962, part 2, p. 143) were dredged from the sea bottom, yet have enlarged meandrine grooves.

c. The sculpture is produced, not during entry into the earth's atmosphere, but (except for the meandrine grooves) in some earlier phase.

It is therefore concluded that ^{most} tektite corrosion cannot be due to action by ground chemicals; that it was already present on the tektites when they reached the earth's surface.

ABLATION OF SPLASH-FORM TEKTITES

It follows that we cannot explain the absence of the marks of aerodynamic ablation on tektites by appealing to corrosion by ground chemicals. Unless these marks have been removed by breakage (e.g. spalling), the tektite must be carrying the marks of aerodynamic ablation. The role of spalling in removing the aerothermal stress shell, as Chapman (1964) calls the portion of the tektite stressed by aerodynamic heating, cannot be denied. It is clear, however, that every unbroken tektite form must carry either spall marks or a place where the effects of ablation are visible.

In the case of the flanged buttons, the results of aerodynamic ablation are clear; but what about the much commoner splash-form tektites? Should we follow Suess in regarding the sculpturing itself as the result of downward passage through the earth's atmosphere?

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Probably not, for the following reasons:

First, as mentioned above, this kind of sculpture, though it of a relatively dense gas may result from gas flow, seems to require turbulent flow. It does not seem to be possible ~~to produce turbulent flow in the boundary layer~~ to explain attack by dense gases of the kind required here under conditions which simulate tektite entry; at least, all efforts to do so have failed so far.

Second, as pointed out by Berwerth (1910) and others, the sculpture observed on meteorites is not really like that on tektites; by comparison, meteorite sculpture seems to smooth the surface, at least if we are thinking on a scale of millimeters.

Third, some of the sculpture on the posterior surface of australites seems to predate the formation of the flanges, as noted above. Conceivably it could represent an earlier stage of aerodynamic ablation; but this is improbable because higher atmospheric density favors turbulent flow over laminar flow. The flanges are the result of laminar flow; if there is to be turbulent flow in descending flight, it should come after the laminar flow; but a small amount of corrosion is observed under the flanges.

Fourth, the sculpture on the Ninninger and Huss (1967) specimens seems to have been put on while the tektite was still plastic. Watson (1935) pointed out the difficulty of heating a mass the size of a tektite all the way through during a meteoric passage through the atmosphere.

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It would require a nearly grazing approach; and would also, probably, mean that the tektites would have to form by the sweeping-off of a liquid layer (O'Keefe, 1963b). This idea has had to be given up (O'Keefe, 1969c) because it cannot be made to fit the microtektite data. Hence the Niningger specimens point to sculpturing at the source.

Similarly, Bouska (1972) found pairs of moldavites in which one had plunged into the other while the specimens were still plastic. The pattern of corrosion is different on the two pieces as if already established when they were joined.

If the Niningger and Huss specimens are examined, it will be seen that in addition to the plastic breaks, they have considerable areas which are bare of all corrosion. ^(Pl 30) These areas may be called bald spots. Is it possible that these bald spots represent the results of aerodynamic ablation?

If we examine the splash-form tektites with this question in mind, we will note that a very large number of them do have a sort of bald spot, where the sculpture seems to have worn away. ^(Pl 26, 34, 27) In museum specimens, this is usually the place where the curator puts the label on. It does not, of course, always appear on broken tektites. On unbroken tektites, the spot is often more easily detected by the sense of touch than by sight; but it is almost always there. In the few cases when it cannot be found, the reason may be that the

tektite tumbled in flight, so that the ablation was evenly distributed over the whole object. 91

Chapman (personal communication, 1973) argues that these bald spots result from spallation; and there can be no question about the fact that this is sometimes true. On the other hand, there also appear to be cases when the bald spot includes some pits in it, as if these had been too deep to be scrubbed off. When these surviving pits are numerous, it becomes evident that the spalled fragment, if any, would have been lacy with holes. It does not seem mechanically plausible that such an object would break off in one piece.

The main point is, however, that ablation on the splash-form tektites must have been much less than that on the australites. This is not a matter of minor details, but of overall form. Where there are spheres among the indochinites, there are lenses among the australites; where there are drops or dumbbells or rods, the australites have the equivalent form but flattened. The flattening is clearly not a matter of deformation while in a plastic condition; it is rather a matter of the loss of some material. There are some tektites outside Australia whose overall form simulates that of the australites (von Koenigswald, 1967, King, 1964a, Chao et al, 1965, Soukenik, 1971b) ; but they are rare. The general rule is that the overall shapes of the splash-form tektites resemble the shapes

which the australites must have had before they were ablated.

We seem to be driven to suppose that the splash-form tektites suffered some kind of ablation (connected with the bald spots) but that this ablation was quantitatively much less than that of the australites.

Furthermore, it appears that the ablation of the splash-form tektites occurred without melt flow, or with only very minor melt flow, as in the case of some rare javanites.

Is it possible to imagine circumstances such that in a single event some of the infalling objects are deeply ablated, losing up to a centimeter in depth, at least some of it by melt flow, while in the same fall (but not in the same area) other objects lose only a millimeter or two in depth, with very little of the loss being due to melt flow? Investigations to attempt to answer these questions are being considered.

MUONG NONG TEKTITES; MICROTEKTITES

The Muong Nong type tektites (Pl. 9, 10) appear to be chunks broken out of an extensive layered mass; their forms do not appear to have any further significance. The Libyan Desert glass (Pl. 26) belongs to this category (Barnes, 1963). The Darwin glass (Pl. 27) and the Aouelloul glass (Pl. 28) are also closely related to the Muong Nong category (Barnes, 1963); they show clear evidence of a layered structure, but it is often contorted.

The overall forms of the microtektites resemble those of the splash-form tektites. They are presumably governed by the same considerations.

BODY SHAPES OF TEKTITES

Underlying the australite flanges, and the pits and gouges of the splash-form tektites are the general body-shapes. Most australites, and many splash-form tektites are spherical. Others are oblate spheroids, rod-shaped bodies, dumbbells, tear drops, or canoes. See Pl. 11, 12, 13. CR

The spheres can obviously be thought of as large drops. For the shapes of the other bodies, Fenner (1934) suggested that rotation had played a major role. This idea has been widely accepted (e.g. Baker, 1959b); but according to an important paper by Tobak and Peterson (1964) it is wrong. They remark that under surface tension, a figure of equilibrium must be rotationally symmetrical around the actual axis of rotation; this rules out both the dumbbell and the (prolate) ellipsoid, because both bodies could rotate stably only around their short axes. Tobak and Peterson deduce that the shapes of splash-form bodies resulted from the breakup of a jet, which was turning slowly or not at all.

CONCLUSIONS

The most important conclusion is that the flanged australites appear to have entered the atmosphere, as Chapman and his coworkers have claimed, at velocities near 11 km s^{-1} , and at angles to the horizon on the order of 30° .

Australites seem to have entered the atmosphere as smooth bodies, usually spherical (since the surfaces under the flanges are smooth).

Splash-form tektites seem to have entered the atmosphere as rough bodies; the roughness, judging from the bent tektites of Nininger, was impressed while the inside of the tektite was still hot and plastic.

It may be that the very different pattern of ablation found on most splash-form tektites (some bald spots but no liquid flow) is connected with differences in initial surface sculpture.

It does not seem likely that tektite sculpture was produced by ground chemicals.

CHAPTER 4

THE INTERNAL STRUCTURE OF TEKTITES: PETROGRAPHY

OVERALL STRUCTURE

Homogeneity of tektite glass

If a typical splash-form tektite is examined in an ordinary thin section, no structure whatever is seen apart from a few small bubbles (vacuoles). Rankama (1965), after a study of 33,000 australites, remarked that the lack of inclusions is highly significant; the point was made earlier by Scrivenor (1933) from scanty data. An unmistakable inclusion of terrestrial soil or rock would of itself settle the question of the origin of tektites; such inclusions are always found in undoubted impact glasses, such as those from Wabar, Henbury, or the Ries Kessel (Chao and Littler, 1962). It is also of great importance to theories of the formation of tektites that they consist for the most part of glass which is homogeneous at the level of a percent or two (Dixon and Meadows, 1968, Hawkins, 1963, Walter, 1965), and has so few vacuoles that it is not ordinarily necessary to crush a tektite in order to get an accurate measurement of its density (at the level of 0.001 g cm^{-3}) (Chapman et al, 1964). It is particularly remarkable that there should be marked homogeneity in individual tektites, and yet striking differences in composition

between tektites found side by side, or even welded together (King and Bouska, 1968). The homogeneity is strikingly illustrated by

Askouri et al (1973), who compare the macroscopic homogeneity of tektites with that of obsidian, and contrast it with the inhomogeneity of impact glasses. Under the microscope it is seen that obsidians have tiny crystals throughout (microlites) which are absent in tektites.

The significance of the lack of crystals was studied by Beall et al (1965) and Wosinski et al (1967); they found that it required cooling in less than about 10 hours for an indochinite; they deduced that the indochinites could not have cooled as parts of a sphere of glass with a radius greater than 90 cm. Yagi (1966b) noted that at 900°C , quartz is the end-product of devitrification experiments on tektites, while at 1000°C , after 48 hours, he got cristobalite and a calcic plagioclase.

Strain polarization

If a whole splash-form tektite, for example a moldavite (Wright, 1915, Barnes, 1960, Soukenik, 1971a), is put in a dish of light machine oil and put between crossed polaroids, then if the tektite is sufficiently transparent, an overall pattern will be seen, due to a condition of internal strain in the tektite as a whole. For a spherical tektite, the pattern is a black Maltese cross; see Pl 42.

The explanation is that the tektite appears to have cooled

rapidly, as a complete body. The outside cooled first, of course; it formed a rigid outer sphere, which fitted over the still-molten interior. Then the interior cooled and shrank. This put the whole interior into a state of tension (of negative pressure). Since this is isotropic, it does not affect the polarized light.

The exterior is pulled inward; accordingly it is in a state of tension in the radial direction. The tension is resisted by compression in the tangential direction, as in a masonry arch, or the dome of a basilica. Hence light which goes through the center of the sphere retains its original direction of polarization, because in the outer part of the sphere it encounters glass which is in compression in both of the two possible directions of the light vector (perpendicular to the direction of propagation). But for a ray which grazes the sphere, passing only through the outer part, the two light vectors, in the radial and tangential directions, encounter different conditions in the glass. Since the glass atoms are pulled apart in the radial direction, the glass behaves, for the radial vector, like a medium of reduced density and hence reduced index of refraction; and vice versa in the tangential direction. If the ray which is coming up through the dish from the lower polaroid (the polarizer) is polarized in either the radial or the tangential direction, there is no net effect on the

state of polarization, and hence the ray is blocked by the second (analyzing) polaroid; this makes the dark arms of the cross. But when the direction of polarization of the incoming ray is intermediate, then the glass resolves the ray into radial and tangential components, which get different lags, and which combine on emerging from the glass to form elliptically polarized light, which does, in part, get through the analyzing polaroid, and makes the bright spaces between the arms of the Maltese cross.

The phenomenon is important because it means that the splash-form tektites cooled as separate objects from a temperature above the annealing temperature (600°C) and did not afterwards lose the outer, compressed shell (e.g. by ground chemical attack). For example, Rost (1967a) showed that the pattern disappears if the outer 3 mm are ground off. The same phenomenon was seen by Wright (1915) in Icelandic obsidians from Hrafninnuhryggur. Hammond (1950) estimated the strains at 735-1220 pounds per square inch (51 to 84 bars). He remarked that cooling at a rate of about 50°C per minute or more was required, especially between 700°C (the strain point) and 600°C (the annealing point). Majmundar and O'Keefe (1967) found that even the details of the strain birefringence around notches could be removed by annealing and then brought back by rapid cooling from 1000°C .

THE INTERNAL STRUCTURE OF TEKTITES: PETROGRAPHY

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Von Koenigswald (1963a) reports a large philippinite (648 g) which broke into at least 124 fragments on cutting, the fragments being pyramidal with the points directed inward. He attributed this to the same kind of stresses. He remarked that in some cases bubbles seem to have formed at the center of the tektite as a result of these stresses; when the bubble is found, the stresses appear to be less.

Chapman (1964) found that there is a strain pattern, visible in polarized light, apparently associated with the heating of australites and javanites in their descent through the atmosphere. He was able to duplicate the patterns by ablating tektite models in a wind tunnel. His calculations and experiments led to the conclusion that the strain pattern should vary in thickness from 2 mm for vertical descent to 4 mm for descent at a shallow angle. The observed patterns indicate that the javanites descended at a steeper angle than the australites. The same stresses are responsible for the frequent spallation of the front surfaces of australites and javanites (cf. also Fenner, 1949). Chapman was not able to trace the effects of strong one-sided heating in other tektites; he attributed this to prompt spallation of the affected zone, combined with attack by ground chemicals.

Barnes (1964c) has pointed out that this structure is not observed in the Muong Nong tektites; it follows that they cooled more slowly, presumably because they were parts of even larger masses.

On the other hand, in Muong Nong tektites one does observe a strain pattern around each individual grain of lechatelierite. This is clearly due to the fact that the lechatelierite has a smaller coefficient of thermal expansion than the glass; hence the glass shrinks all around it and compresses it.

Structural anisotropy

Raman (1950a) drew attention to a different kind of birefringence which he first observed in Libyan Desert glass. Under very strong illumination (full sunlight) Raman found weak birefringence which followed a set of plane parallel layers in the glass. He considered that they could not be a strain birefringence because, given the very low thermal coefficient of expansion of silica glass such as Libyan Desert glass, it is hard to see how strain birefringence could be set up. He found similar birefringence in artificial silica glass, clearly related to the directions along which the silica glass had been worked. Raman considered that this birefringence was due to the fact that the glass yields to the stresses of working, not only by breaking oxygen bonds,

but also by deforming the SiO_4 tetrahedra. He called the result "structural anisotropy," distinguishing it sharply from strain isotropy. In later papers (Raman, 1950b, 1950c) he found structural anisotropy weakly manifested in commercial rolled plate glass; he attributed it to deformation of the glass as it passed through the rollers. The implication of Raman's finding is that the Libyan Desert glass was sheared, while being cooled, along a set of parallel planes. The pressures used between the rollers in a typical plate-glass factory are of the order of

Numbers.

SMALLER STRUCTURES

Lenticules

From the petrographic standpoint the most important tektites are those of the Muong Nong type, which have been reported from Indochina by Lacroix (1935c), Barnes (1964b), Fontaine (1966); from the Philippines by Barnes (1964b); from Czechoslovakia by Barnes (1964b) and Rost (1966); and from Texas by Barnes (1964b). In relatively thick sections, around 500 micrometers, they show a phenomenon which Barnes calls the shimmering structure. The comparison is with the shimmering of a distant landscape seen through hot, turbulent air. It is clearly due to regions of varying index of refraction, for which I propose the name lenticules because in general

the small regions are drawn out into lens-like shapes, as seen under the microscope, a few tens of micrometers in width, and hundreds of micrometers in length. They are most clearly seen when the diaphragm is stopped down, or when an occulting object is moved through the light-path. Under these circumstances, the boundaries of the lenticules appear quite sharp, as if the Muong Nong tektites were really composites of a large number of small glass bodies.

In some Muong Nong tektites, the lenticules are bounded in part by void spaces (Plate ⁴³ ~~000~~); a similar thing is seen in the Libyan Desert glass in some parts. CR

Dr. L. S. Walter kindly polished some Muong Nong tektites, and then demonstrated that the boundaries of the lenticules can be shown by attack with HF (Plate ⁴⁴ ~~000~~). He also showed, in an unpublished work which he kindly permits me to quote, that the boundaries of the lenticules can be traced by variations in the chemical composition. CR

Barnes (1964b) suggested that the lenticules, which he was the first to recognize, were formed by the shock melting of mineral grains in a hypothetical parent rock. He noted the cusped (spiny) form of the voids which bound the lenticules in some Muong Nong tektites, and suggested that these were relics of incompletely rounded voids between the original sand grains of the parent rock.

The suggestion of Barnes was taken up by O'Keefe and Adler (1966) who noted that the hypothetical parental sandstones would be expected to consist of grains of distinct minerals, chiefly quartz; they showed, however, that the lenticules do not have the composition of any mineral, but instead, as found by Walter, ^(Fig 4-1, 4-2, 4-3) they have the composition of homogeneous glasses, at least qualitatively like the bulk composition of the tektite.

They suggested that the Muong Nong tektites are similar to terrestrial welded tuffs. A welded tuff is a deposit of volcanic ash, often largely glassy, which was laid down hot (above 800° C, according to Boyd, 1961). Under pressure from overlying layers, the particles of ash (shards) have deformed plastically so as to close the voids. The result, under certain conditions of pressure and temperature, is a solid mass of glass, in which, however, the outlines of the original shards may be visible. The suggestion that the Muong Nong type tektites might be a sort of welded tuff was laid before the late Hoover Mackin, who remarked that the lenticules do not really resemble the shards in a welded tuff, because they do not have the Y-shapes which are a prominent feature of terrestrial welded tuffs. These Y-shapes result from the spiny form of the terrestrial shards. Their absence in the lenticules seemed to us (O'Keefe and Adler, 1966) to mean that the parent bodies of the lenticules were

rounder than the terrestrial volcanic shards.

A few months after this remark was published, the microtektites were discovered by Glass (1967). They correspond in size and shape to the hypothetical parent bodies of the lenticules; in addition, Glass has shown that the lenticules from a given tektite show a sequence of compositions like that observed in the corresponding microtektites (see Chapter 6). It is difficult to doubt that there is some connection between the microtektites and the lenticules.

Underneath the flanges, on the original outer surface of the australites, Barnes (1962b) detected some small objects of higher index of refraction. Glass (verbal remarks) says that these turn out to be the denser glasses which he finds in tektites.

Schlieren *Striae*

In splash-form tektites, the lenticules as such are rarely seen (but note Glass, 1969b, a lenticule in an australite); instead, one sees or schlieren (pl 20) *Striae* schlieren, i.e. contorted layers of varying refractive index. These seem to grade into the parallel systems of layers which are seen in Muong Nong tektites. The ~~schlieren~~ *Striae* ordinarily meet the surfaces of the tektites abruptly (Hubbard et al, 1956); this is significant because it does not fit the idea that the splash-form tektites were formed by some kind of condensation process from the gaseous state.

On the front surfaces of australites, the ^{striae}schlieren do not usually meet the surface abruptly, except at the center. Instead, they curve aside and meet it at a very shallow angle. The obvious explanation is that given by Chapman, namely that the front surface was molten, and was dragged to the rear by aerodynamic forces to form the flanges. This explanation is generally satisfactory; but van der Veen remarked that in the photographs of Dunn (1912a) it is clear that in some cases the surface sculpture cuts through the ^{striae}schlieren, particularly toward the edge of the tektite.

Within the australite flanges, the ^{striae}schlieren are coiled in a way which clearly reveals how the flange has formed. It is curious that the flanges of australites show evidence in this way of being much more tightly coiled than either the models of australite ablation produced by Chapman et al (1962) or the flanges of javanites (von Koenigswald, (1963b). Within the flanges the ^{striae}schlieren often become wavy; the same appears in the models.

Many tektites, particularly indochinites, have long tails. The ^{striae}schlieren in the tails are drawn out parallel to the axis of the tail.

Bubbles

Statistics on bubbles in tektites were put together by Aghassi (1962). Lacroix (1931a) noted that the bubbles are rounded in the round portions of the splash-form indochinites, and are drawn out into ellipsoidal forms in the stretched tails of indochinites. He remarked that bubbles in terrestrial obsidians are normally drawn out

if the silica content is greater than 70%; he inferred that the temperatures of formation of indochinites must have been higher than those of obsidians, so that the viscosity could be lower.

Hawkins (1963) found by furnace experiments that bubbles in simulated tektite glass belong to two types; the small bubbles, which show a steep gradient on a size-frequency plot, correspond to the original intergranular spaces; while the large bubbles, with a shallow gradient, correspond to escaping gases. He traced this to the effects of the critical bubble size: since surface tension exerts more pressure as the bubble gets smaller, it follows that for any given pressure in the bubbles, say that due to vapor pressure of some constituent, there is a size below which the bubbles are unstable and shrink, while above it they grow. Hawkins found only the small regime in most tektites; in the Darwin glass he found both.

INCLUSIONS

Lechatelierite

The commonest inclusions in tektites are small bodies of low-index glass which were shown by Barnes (1939) to be
(*pl.*
lechatelierite (silica glass)). They are of silt size, i. e. somewhat smaller than typical sand grains. In Muong Nong tektites they tend

to be accompanied by clusters of bubbles whose size varies greatly from one tektite to another. The lechatelierite bodies themselves tend, in Muong Nong tektites, to be nearly equant, and brownish in color. In splash-form tektites, the lechatelierite is no longer equant; it tends to have long tails, drawn out parallel to the schlieren and often contorted; the length may be up to half a millimeter (Barnes, 1939).

Around the lechatelierite particles the glass shows a pattern of strain birefringence, which results from the difference in thermal coefficient of expansion, and cannot be removed by annealing.

Barnes (1962b, 1963b) has drawn attention to the fact that on many tektites, and especially on the posterior surfaces of australites, the lechatelierite inclusions are more numerous than elsewhere in the glass; and the flow structure around them looks as if they had been pushed down into the glass. He calls these "fingers."

Walter (1965) found coesite in these portions of a Muong Nong tektite from Phaeng Dang. He studied the shapes of the crystals further (Walter and Sclar, 1967, unpublished) under a scanning electron microscope. Pellas (private conversation) found none in tektites from Muong Nong itself. Chantret et al (1967) reported that the brown inclusions contained α -quartz, calcic plagioclase (?) and possible hypersthene. They stated that the quartz is not detrital.

Relative to the matrix, the inclusions are enriched in Si, depleted in Al, K; Fe, Mg, Ca are unchanged.

Quartz

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Quartz is found in some Muong Nong tektites (Barnes, 1963a). It is anhedral, with some rounding. In Aouelloul glass, it is often cracked; the fragments, however, retain the same crystallographic orientation; evidently the crystals were broken in their present locations, and there was relatively little flow thereafter.

Barnes (1964b) notes that the layered structure observed in Muong Nong type tektites is sometimes interrupted by miniature faults. The faults are usually welded shut, and occasionally are filled with tektite glass. Along the faults, crystals, usually of quartz, are observed. From their shape, the crystals are judged to be detrital, in most cases; there is some evidence of very small euhedral quartz crystals (5 micrometers in diameter) which seem to have resulted from devitrification of the glass along the fault. Barnes reports another unidentified mineral, which forms triangles and rosettes, up to 50 microns across, with weak or no birefringence.

Rays

In some tektites, Barnes (1964a) has noted some long narrow structures, which he calls "rays," protruding from tektite bubbles. They are usually of lower index of refraction than the matrix glass.

Heavy minerals

By crushing Muong Nong tektites and using heavy liquids to separate the denser fractions, Glass (1970b, c) has found crystals of zircon, chromite, corundum, rutile, and monazite. The crystals are in general fractured, although enclosed in a complete, unbroken envelope.

Zircons and baddeleyite

Baddeleyite (ZrO_2) was noted in the Martha's Vineyard tektite by Clarke and Henderson (1961); it was found in Aouelloul glass by El Goresy (1965), and in a Georgia tektite by King (1966a). El Goresy stated that the baddeleyite was the product of the disintegration of zircon (ZrSiO_4); in fact, zircons are also seen in tektites (Glass, 1970b). El Goresy noted that the transition from zircon to baddeleyite plus silica takes place at 1676°C , and concluded that the tektites had reached this temperature. Kleinman (1969a) quoted El Goresy on this point when she found baddeleyite in Libyan Desert glass. The conclusion was criticized by Clarke and Wosinski (1967) who furnished clear evidence that zircon can be attacked by liquid glass at temperatures as low as 1500°C , with the formation of baddeleyite. The contrast between melting and solution in the disappearance of solid phases is a recurrent theme in glass-making.

Nickel-iron spherules

Chao and coworkers (Chao et al, 1962) discovered nickel-iron spherules in philippinites from Santa Isabela. (The earlier claim of Spencer (1933c) to have found them in australites and Darwin glass has never been confirmed.) Others were found in indochinites from Dalat (Chao et al, 1962). The spherules were accompanied by inclusions of troilite and schreibersite, which are typical of iron meteorites. Further studies were reported by Chao et al (1964); the sequence of trace elements corresponds to that in iron meteorites. Subsequently, Chao et al (1966a) reported nickel-iron spherules in Aouelloul crater glass.

Brett (1966, 1967) has drawn attention to a law which governs the appearances of these spherules, and which seems to distinguish between tektites and impact glasses such as Wabar and Henbury.

Nickel-iron spherules formed by meteorite impact in the earth's atmosphere are very rich in nickel, and are surrounded by an iron-rich halo. Those formed in tektites have normal nickel abundance and no halo.

The meaning of Brett's Law is discussed in Chapter 6. Chao et al (1966a) noted an iron-rich region around the Aouelloul nickel-iron spherules, whose nickel content, however, goes only up to 9%. O'Keefe pointed out that not only iron but also other cations were enriched in this region, as if it were a local patch of relatively

low-silica glass.

Reid et al (1964) showed that although small iron spherules can be produced in tektite glass by heating under reducing conditions, the synthetic spherules do not have the same sequence of trace elements as meteoritic iron.

Magnetite

Magnetite has been reported by Vorob'yev (1959a), Kleinman (1967), and by Fechtig and Kleinman (1967). Vorob'yev's particles were on the outside, and Kleinman found hers by grinding, so that it was hard to be sure that they were really inside. Doan has recently tentatively identified the black particles mentioned by Clayton and Spencer (1934) as titano-magnetite, confirming a remark of Kleinman. The crystalline form could not be traced. Although the particles were deep inside the glass, Doan found evidence that atmospheric gases penetrate the Libyan Desert glass; hence it is possible that the iron was oxidized on the earth. In a number of cases, the magnetite bodies have a core of metallic iron.

SUMMARY

Tektites are generally homogeneous glasses usually without crystalline inclusion or bubbles amounting to as much as 0.1% of the total volume.

Muong Nong tektites in particular and to a less extent other tektites appear to be composed of small glass particles (lenticules) which have been welded together. The lenticules may have been microtektites before welding.

Tektites cooled as separate bodies of at least roughly their present dimensions.

There are inclusions in many tektites of minerals which appear detrital.

Coesite is reported but disputed.

Nickel-iron spherules are found, resembling meteoritic spherules.

PHYSICAL PROPERTIES OF TEKTITE GLASS

The physical properties of tektite glass are interesting and significant in themselves, as well as in relation to theories of tektite formation. This chapter is divided into

Mechanical properties, including acoustic properties.

Optical properties.

Electromagnetic properties.

Thermal properties.

The logic of putting the optical properties next to the mechanical properties, instead of with the electromagnetic properties of which they are really a part, is simply the close relation between specific gravity and refractive index, as well as that between polarization and strain.

The thermal properties include thermal coefficients of other properties.

MECHANICAL PROPERTIES

Specific gravity and porosity

The specific gravity of tektite glass ranges from 2.21 g cm^{-3} for Libyan Desert glass (Clayton and Spencer, 1934) to over 2.80 g cm^{-3} for the heaviest of the bottle-green microtektites (Glass, 1972b). Because of the existence of porosity in tektite glass, the most precise

measurements must be made on crushed specimens. However, Scheiber (1970) showed, by comparing with the refractive index, that the bulk measures of specific gravity are usually reliable within a few units in the third decimal place, unless there is obvious and conspicuous porosity. Barnes (1939) finds total bubble volumes of 0.00023% and 0.15% for two bediasites. This means that statistical studies can be made on the bulk specific gravity; it also gives a numerical measure of the freedom from bubbles of tektite glass in general. This measure is significant when tektites are studied from the point of view of glass-making (Chapter 8).

The frequency distribution of tektite specific gravity at particular localities was studied by Chapman et al (1964) who found that the frequency-distribution of densities is markedly different at different points even in a relatively homogeneous area such as Australia. On the other hand, they were able to use this method to relate some widely-separated places such as southwest Australia with the Philippines, or Java with Charlotte Waters, Australia. They found that the density histograms for points less than 100 kilometers apart were generally indistinguishable, which gives an idea of the sharpness of the streaky structure of the Australasian strewn field.

King (1964c) studied the specific gravity of 329 bediasites.

His graphs show that in the southern part of the area, around Muldoon, the mean specific gravity is about 2.35, only a little higher than Georgia tektites (2.34); in the middle of the region it is 2.37; and in the north (Grimes County) 2.385 .

Martin (1934b) made a large number of measures of specific gravity throughout the Australasian strewn field. Baker and Forster (1943) measured specific gravities throughout Australia. In particular, they found indications that for Port Campbell australites, the flange fragments had slightly lower specific gravity (2.387) than the body fragments (2.396).

The specific gravity as a function of silica content is shown in Fig. 5-1. It was noted by Tilley (1922) and later by Barnes (1939) that this relation is not precisely the same as the relation of silica content to specific gravity in terrestrial igneous glasses; the latter are lower by about 0.01 in specific gravity than tektites of the same silica content, presumably because tektites contain more of the heavy, divalent oxides, and less of the lighter, monovalent alkali oxides.

From Fig. ⁵⁻¹ it is clear that the clan of the high-magnesium tektites and the bottle-green tektites is even higher in specific gravity than the general run of tektites, presumably because of the replacement of Al_2O_3 , Na_2O and K_2O by MgO and FeO .

PHYSICAL PROPERTIES OF TEKTITE GLASS

The equations of the three lines of Fig. 5-1 are each in the form

$$\text{Sp. gr.} = 2.346 - k_n(S - 79.3)$$

5.1

where

$$k_1 = 7.73 \times 10^{-3}; k_2 = 11.79 \times 10^{-3}; k_3 = 16.07 \times 10^{-3};$$

S is the silica content in weight percent. The coefficient k_1 holds for the high-silica tektites; k_2 for the normal tektites; and k_3 for the high-magnesium branch.

Note that almost all hand specimens of tektites as they are usually spoken of (without the Aouelloul glass, Darwin glass, microtektites, Libyan Desert glass, or the high-sodium variety) fall between a silica content of 68% and 82% along the line for normal tektites.

The problem of the relation of specific gravity to chemical composition has not been studied for tektites, although for commercial glasses it has been found (Morey, 1954, p. 221) that the reciprocal of the specific gravity, i.e. the specific volume, is approximately additive for glasses. It would probably be useful to compare calculated glass densities with observed densitites, because the exact density of a glass depends both on its composition and on its heating history; see below. To make the comparison, the specific volume is needed for FeO; it is not given by Morey.

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PHYSICAL PROPERTIES OF TEKTITE GLASS

The principal sources for specific gravity data in addition to those quoted above are the chemical analyses. For the moldavites and the more silicic tektites these are well summarized by Rost (1972). For tektites in the main range, the most important source is Chapman and Scheiber (1969b). For some australites, see Cuttitta et al (1964b); for indochinites and philippinites, the tables of Schnetzler and Pinson (1963, 1964a) are particularly useful. For bediasites, Chao (1963b) is the best source; for other North American tektites, see Cuttitta et al (1967). For Ivory Coast tektites, Chapman and Scheiber (1969b) and Cuttitta et al (1972) are the principal sources. For the bottle-green microtektites, the source is Glass (1972b).

Hardness

Suess (1900) reports measurements of moldavite hardness on the corundum scale by Rosiwal; the hardness was 29.5 and 31 on two specimens, compared to 18.2 and 19.8 on two commercial glasses and 34, 35.6 on two obsidians. On the more usual Moh scale, the hardness is between 6 and 7 (Baker, 1959b); it approaches 7 for the most silicic tektites such as Darwin glass. Bouška and Povondra (1964) measured microhardness on some moldavites with the Haneman apparatus; the results were from 900 to 1200 $\text{g}/\mu\text{m}^2$. Weiskirchner

u
Shank

(O'Keefe and Weiskirchner, 1970) finds that the hardness so measured decreases with load, increases with silica content, and shows significant mechanical hysteresis.

Strength

Centolanzi (1969) found that the ultimate tensile strength of tektite glass varies between 0.6 and 1.0 kilobars (one kilobar is 10^8 newtons per square meter).

Elastic constants; acoustical wave velocities

Soga and Anderson (1967) tabulate the elastic constants for two tektites (See Table 5-1). They obtained the wave velocities by finding the resonant frequencies of small glass spheres; the other parameters are deducible (given the density) by standard formulas (Jeffreys, 1959, pp. 1-4).

Table

Crack formation; internal energy

Levengood (1966) measured the flaws which radiate from cracks in tektites, as in other glasses. The length and number of flaws are related ^{respectively} to the internal energy and Young's modulus. The flaws themselves might conceivably be the "mesh of small cracks" whose existence was postulated in Chapter 3 to explain the cross-sectional outline of the meandrine grooves.

Destruction by micrometeorite impact

Gault and Wedekind (1969) find that a tektite will be shattered if

as much as 1 joule per gram is delivered to the tektite either by a single impact or by several impacts. The figure is surprisingly low compared with the energy required to produce a crater of dimensions like a tektite in a semi-infinite solid. The difference is due to the trapping of shock waves within the tektite body.

OPTICAL PROPERTIES

Refractive index

The refractive index, normally given as that of the sodium D line at 589.0 and 589.6 nm, and symbolized n_D , is closely related to the specific gravity. A similar plot has been prepared (Fig. 5-2) of n_D against silica content. As with the specific gravity, three trends appear to be represented, each described by an equation of the form

$$n_D = 1.489 - c_n (S - 79.3)$$

5.2

where c_n has the value .001429 for the high-silica tektites,

0.002840 for the main range; and 0.003703 for the high-magnesium clan.

It follows that the refractive index can be regarded as a function of the density, with the relations

$$n_D = 1.489 + \frac{c_n}{k_n} (\rho - 2.346)$$

5.3

where $c_1/k_1 = 0.1849$; $c_2/k_2 = 0.2408$; $c_3/k_3 = 0.2304$.

Durrani (1971) found

$$n_D = 1.480 + 0.237 (\rho - 2.346)$$

5.4

which fits reasonably well except for the high-silica materials.

Formulas exist (Morey, 1954) for the calculation of the refractive index from density and chemical composition. They seem to work well for the more silicic tektites; at the silica content of the Ivory Coast tektites, discrepancies of the order of 0.01 are found between calculated and observed refractive indexes.

The refractive index varies considerably within individual tektites. In typical splash-form tektites, the wavy structure (schlieren) correspond to changes of 0.001 in the refractive index (Chao, quoted in Rost, 1972). The waves have a physical thickness varying between 1 and 500 micrometers. Barnes (1939) notes an individual bediasite (by no means typical) in which the index of refraction ranged from 1.483 to 1.512. By contrast, in a group of 79 bediasites, the average index ranged only from 1.489 to 1.509. Barnes later (1964c) found that at individual Muong Nong deposits (each of which may represent an individual block of incoming glass) the refractive index tends to vary by 0.010 to 0.015. Rost (1972, p. 32) insists that even in moldavites, there is always a homogeneous basic vitreous substance which dominates in volume over the striae and other inhomogeneous parts. Hubbard et al (1956) note an australite in which the index of refraction varies from 1.504 to 1.524 over a small cross section.

The measurement of 1.538 for an individual moldavite from Senohrady by Novacek (1932a) was discarded by Adamovska (1967); ^{and Adamovska}

it is not used here. The silica content was 74.9%.

Dispersion

For Libyan Desert glass, measurements by Clayton and Spencer (1934) and Schwantke (1909) are shown in Table 5-2.

Polarization and strain

Although tektites are glasses, and hence never show strong effects in polarized light, yet they almost always show detectable birefringence resulting from strain; this is valuable as an indication of structure and history. The discoveries of Wright, Barnes, Raman and others have been discussed in Chapter 4.

The ratio of birefringence to stress is the stress-optic coefficient, which is normally of the order of 3 brewsters; a brewster is $10^{-13} \text{ cm}^2 (\text{dynes})^{-1}$, or in S.I. units $10^{-12} \text{ m}^2 \text{ N}^{-1}$. Centolanzi (1969) measured the stress-optic coefficient of tektite glass. His paper is obscure; it appears that he used a thin disk of glass of specific gravity 2.43, stressed by compression applied at two points diametrically opposite one another at the edges of the disk. Using a standard formula for the stresses at the center of the disk, he found from his measurements a parameter Z, which he called the stress-optic coefficient, such that

$$Z = \lambda / C$$

where λ is the wavelength of the light, and C is the stress-optic

(5.5)

2/

coefficient as the term is generally used. Centolanzi's stress-optic coefficient is $1/2$ the quantity called the "fringe value of the material" by Frocht (1941, p. 159). He found $Z = 177$; taking 546.1 nm for the wavelength of the light, and allowing for the difference of units this implies 3.2 brewsters.

The numerical amount of the phase-shift due to stresses was measured in some moldavites by Soukeník (1971a). His units are nanometers of optical path-difference per centimeter of path length (Morey, 1954, p. 167). In S.I. units, Soukeník found strains averaging 10,000 (nanometers of optical path-difference per meter of path length) but rising in one case to 55,500; ellipsoidal pieces tended to have about 20% less strain. He found that strain increases systematically with size. Obsidians, by contrast, show very little strain.

Soukenik's strains, using Centolanzi's stress-optic coefficient, would correspond to stresses of 3×10^6 to $18 \times 10^6 \text{ Nm}^{-2}$ (30 to 180 bars). Hammond (1950) found stresses of 5×10^6 to $8.5 \times 10^6 \text{ Nm}^{-2}$ (50 to 85 bars) by similar methods.

Rost demonstrated (1972, p.66) that when a strained tektite is broken, the strain reorients itself in accordance with the new shape of the fragment. He denies that the figures seen between crossed polaroids can be used as an argument against the loss of the outer portions of the tektite (e.g. by corrosion). Centolanzi (1969) puts the matter quantitatively; the reduction of the strain in a sphere

to 20% of the initial value requires the reduction of the radius to $1/2$ of the initial value. Majmundar and O'Keefe (1967) found that the birefringence around the notches in moldavites can be made to disappear by annealing; if the specimen is reheated and quenched by an airblast, the strain reappears in the same pattern as before; and the strain around an artificial notch is indistinguishable from that around natural notches. This means that the strain around the notches does not carry a memory of the way in which the notch was made; it is determined by the shape of the notch and the overall strain in the tektite.

Spectrum

The tektite absorption spectrum is shown in Figs. 5-3 and 5-4. The absorption increases greatly toward the longer wavelengths. The breaks between Fig. 5-3 and Fig. 5-4 and between the two curves of Fig. 5-4 each correspond to a scale increase (going toward longer wavelengths) by a factor of about 10.

Fig. 5-3 covering the range from 0.3 to 4 micrometers is redrawn from Stair (1955). The ordinate is transmittance (transmitted light / entering light, I/I_0) for a bediasite (curve labelled 4) and an australite (curve labelled A), each about 0.5 mm in thickness. The high ultraviolet absorption and the band at 1200 nm are due to FeO ; the notch at 2800 nm is due to water (more exactly, OH) in the glass.

Libyan Desert glass has the same ultraviolet cut-off, but its transmittance is consistently high up to 4 micrometers. Similar spectra in the region from 0.3 to 2.5 micrometers were found by Cohen (1958); Cohen plots the absorbence, A , given by

5.6

$$A = -\log_{10} (I/I_0)$$

Gilchrist et al (1969) obtained spectra similar to Stair's, and utilized the band at 2.7 micrometers to obtain the water content of tektites (see Chapter 6).

In the far infrared, from 4 to 7.5 micrometers, the curve is based on Perry and Wrigley (1967) who used a 65-micrometer thin section; from 7.5 to 24 micrometers it is based on Kadushin and Vorob'yev (1962), who powdered the tektites and put the powder between slabs of NaCl or KBr. The particle size was less than 7 micrometers; this technique let them get some light through even this very opaque material. Houziaux (1956) obtained a qualitative curve for this region. He states that the fundamental vibrations of the silicon tetrahedron are at 8.5 micrometers (an inflection only in the observed curves), 9.5, 12.7, and 21.6 micrometers. At 10.6 micrometers he notes a band in the long-wavelength wing of the band at 9.5 micrometers; this he attributes to oxides of alkalis or alkaline earths.

The reflection spectrum was observed by Perry and Wrigley (1967).

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See Fig. 5-5. They found peaks at 457 and 1060 cm^{-1} (21.9 and 9.4 micrometers) which correspond to the chief depressions found in the transmittance by Kadushin and Vorob'yev(1962). These are essentially the famous reststrahlen, or residual rays, of fused silica (Wood, 1934, p. 516, 517). Perry and Wrigley also found weaker bands at 77,000, 94,000, and 1,200,000 m^{-1} (770, 940, and 1200 cm^{-1}), which can be seen in absorption in the curve of Houziaux. By comparison with the reflection spectrum of fused silica, they showed that the peaks at 45,700, 77,000, 1,060,000, and 1,200,000 m^{-1} (457, 770, 1060, and 1200 cm^{-1}) were due to silica. They further showed that the reflectivity between 60,000 and 90,000 m^{-1} (600 and 900 cm^{-1}) is largely due to Al_2O_3 . In ^egeneral, the reflectivity measurements appear to be considerably more expressive than the transmission measurements for wavelengths greater than 6 micrometers.

Emissivity

The maximum emissivity of tektite glass is given by Chapman and Larson (1963) as 0.91 for $n = 1.50$.

Color

Most tektites are black; Georgia tektites and moldavites from Bohemia are various shades of olive green (Rost, 1972). Moldavites from Moravia tend to be brown; however, this is a statistical rule. There are light olive-brown bediasites from the

PHYSICAL PROPERTIES OF TEKTITES

Muldoon area (Barnes, 1951). Aouelloul glass is yellowish-gray by transmitted light, and Darwin glass is gray. Usually tektites show shades of brown or green, rather than gray, on thin edges; this helps to distinguish them from obsidians. Thorpe and Senftle (1964)

attribute these brown shades to submicroscopic spherules of Fe_2O_3 or metallic Fe.

Microtektites are generally brown, black or yellow, or clear (Cassidy et al, 1969). Among them, however, are the magnesium-rich bottle-green tektites. These may have up to 0.2% Cr_2O_3 (Glass, 1972b) to which their color may be due.

It is puzzling that the "poisonous green" moldavites of Netolice (Bouska and Povondra, 1964) are rich in MgO , but not especially rich in Cr. Morey (1954, p.456) notes that the coloring effect of Cr in glass may depend on the other oxides present.

ELECTRICAL AND MAGNETIC PROPERTIES

In this section, the notation and units of Stratton (1941) are followed. These are the same as the S.I. units used throughout this book. The system is an MKS system in which the units have been so chosen as to eliminate factors of 4π in Maxwell's equations, at the cost of introducing them in the Coulomb equation and the analogous equation for the attraction of a magnetic pole. For volts, amperes, and coulombs, the system is the same as the practical system, and

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very different from the cgs electromagnetic units generally used in scientific work.

Dielectric constant (specific inductive capacity)

In a non-ferromagnetic material such as tektite glass, when conductivity can be neglected, the specific inductive capacity ϵ/ϵ_0 (i.e. the permittivity ϵ , relative to that of free space, $\epsilon_0 = 8.854 \times 10^{-2}$ farad/meter) is very nearly equal to the square of the refractive index. It is the quantity usually called the dielectric constant; it is obtainable at optical frequencies from the data already given, and is about 2.25.

In the near infrared, Perry and Wrigley (1967) give the index of refraction, n (Fig. 5-6). Here, however, the conductivity cannot be neglected; we have

$$n^2 - \kappa^2 = \epsilon/\epsilon_0$$

(5.7)

where κ is the imaginary part of the index of refraction; κ is also graphed by Perry and Wrigley.

In the radiofrequency region, the specific inductive capacity has been measured directly by Olte and Siegel (1961); they find 4.2 for the Libyan Desert glass, and 6.0 to 7.4 for some indochinites and australites. A single moldavite gave 6.1. The transition from values around 2.25 to values of 5 or more takes place at the frequency of the principal resonances, at 9 and 22 micrometers; it can be followed in the curves of Perry and Wrigley (Fig. 5-6).

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Electrical conductivity

The electrical conductivity, σ , of tektite glass is related to the imaginary part, κ , of the index of refraction by the equation

$$n\kappa = \frac{\mu\sigma T}{\mu_0}$$

where T is the period of the vibration, σ the conductivity, μ the magnetic permeability, and μ_0 that of free space. The ratio μ/μ_0 is effectively 1. Hence the conductivity can be deduced from the curves of Perry and Wrigley for the frequencies corresponding to the resonance vibrations.

For lower frequencies, the resistivity (reciprocal of the conductivity) has been measured as a function of temperature by Hoyte et al (1965) on synthetic glasses which simulate tektite composition. At 300°C, the resistivity ranges from about 10^{13} ohm-meters (10^{15} ohm-centimeters) in Hoyte et al (1965) for a moldavite, down to 3×10^{12} ohm-meters for a javanite. Their measures can be represented within 15% by the following formula:

$$\rho = 0.192 \times 10^{-12} r \pm .016$$

where r is the percentage of Na_2O in the analysis. The unit here is mhos/meter.

Magnetic permeability; magnetic susceptibility

The S.I. units are so chosen that the magnetic permeability, μ_0 of free space is $4\pi \times 10^{-7}$. The quantity which is called the

5.9

permeability in the familiar cgs emu system is then equal to Stratton's specific magnetic permeability, μ/μ_0 . The magnetic susceptibility χ_m is given by

$$\chi_m = \mu/\mu_0 - 1$$

In practice, some authorities (Morey, 1954) use $\chi_m/4\pi$ which is called the volumetric susceptibility. Others, including those who have written on tektites, use $\chi_m/4\pi\rho$, where ρ is the specific gravity; unfortunately this may be called the specific susceptibility, though it is different from χ_m . We shall call $\chi_m/4\pi\rho$ the mass susceptibility. Finally, some authorities (Hodgman, 1962) use the molecular susceptibility, $M\chi_m/4\pi\rho$, where M is the molecular weight.

It turns out that the mass susceptibility of tektite glass is generally less than 10^{-5} , so that $\mu/\mu_0 = 1$, with an error of less than 300 ppm; this justifies our previous assumption that the glass could be treated as non-magnetic in calculating the index of refraction or the dielectric constant.

Senftle and Thorpe (1959) found that the mass susceptibility $\chi_m/4\pi\rho$ varies linearly with the iron content. Their Table 2 seems to be represented by the following formula

$$10^6 \chi_m/4\pi\rho = -0.88 + 1.43 f$$

where f is the percentage of iron oxide, with all iron as FeO.

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The unit of their table is emu g^{-1} per gram; the quantities resulting from the present units are numerically the same as those used by Senftle and Thorpe, but are dimensionless. The chemical analyses which they used showed a considerable range in ferric-ferrous ratio, which was not reflected in the observed magnetic susceptibility; they suggested that in fact the iron is present primarily in the ferrous state. Thorpe et al (1963) drew similar conclusions from the analysis of bediasites; the data from their work is shown in Chao (1963b); it suggests an equation of the form

$$\chi_m/4\pi\rho = -0.4 + 1.61 f$$

over the range from $\chi_m/4\pi\rho = 3$ to 8 with a scatter of only a few tenths in $\chi_m/4\pi\rho$. In microtektites, Senftle et al (1969) found a similar relation.

Magnetic intensity

Early investigations showed no detectable magnetic intensity in tektite glass, at the level of about 10^{-4} emu per gram. (To convert measurements in emu g^{-1} to S.I., multiply by 10^3). Booker and Harrison (1966) set an upper limit of 10^{-7} emu g^{-1} . De Gasparis et al (1973) found evidence of natural remanent magnetism (NRM) in tektites of the Muong-Nong type, although not in the splash-form tektites. According to them, the intensity was between 10^{-7} and 10^{-6} emu g^{-1} . The magnetism was blocked at 500° to 560°C (i.e.

5.12

disappeared when the specimen was heated to this temperature). This indicated that the magnetism could not be isothermal remanent magnetism (magnetism due to a brief exposure to a strong magnetic field). They also found that there was no detectable change in the magnetism due to prolonged heating at 100 °C, followed by cooling in a field of one oersted (about 80 amperes per meter, in S.I.) which is the order of the strength of the earth's field. This, they felt, eliminated viscous remanent magnetism (a slow drift with time toward alignment with the earth's magnetic field) and chemical effects. The behavior resembled that of thermal remanent magnetism (magnetism acquired by cooling from above the Curie point). De Gasparis et al conclude that the magnetism resulted from the cooling of the tektites in the earth's magnetic field.

On the other hand, Nagata (1961) pp. 259-269 points out that there are at least theoretical reasons for believing that lightning could produce a form of remanent magnetism called anhysteretic remanent magnetism, with properties much like those of thermal remanent magnetism. Although terrestrial lightning is observed to produce magnetism which is more easily erased than thermal remanent magnetism, Nagata's remarks indicate that lightning remains a possibility. Note also that one of de Gasparis's

specimens was more strongly magnetized than would be expected from the earth's magnetic field.

THERMAL PROPERTIES

Coefficient of thermal expansion(linear)

From the curve of Hubbard et al (1956) one would scale a value of 40×10^{-7} for the linear coefficient of thermal expansion between 100°C and 500°C . Chapman (1964) gives 7×10^{-7} for silica, 29×10^{-7} for a tektite with 80% SiO_2 , and 42×10^{-7} for a tektite with 65% SiO_2 . Centolanzi (1969) gives 33×10^{-7} for a tektite of specific gravity 2.43 .

Hubbard et al find that the rate of expansion diminishes markedly between 500°C and 650°C ; they identify 650°C as the critical temperature. This temperature is more generally known as the transformation temperature, T_g (Jones, 1971). It is believed that as glass cools from a melt, the atoms are at first able to rearrange themselves; but at the transformation temperature they lose this property; the arrangements then existing are frozen in, and further changes consist of a decrease in the oscillations around points, but not in further movement. Since the transformation temperature is associated with the annealing process, it is important to note that Centolanzi (1969), presumably quoting

PHYSICAL PROPERTIES OF TEKTITES

measurements at Corning Glass Works, identifies the annealing range as $900 - 950^{\circ}\text{K}$, i.e. $630 - 680^{\circ}\text{C}$. These figures are presumably for australites; for philippinites Heide and Brückner (1971) on other grounds find T_g to be in the range $850^{\circ} - 950^{\circ}\text{C}$, while for moldavites they find that the transformation zone is from $900 - 1030^{\circ}\text{C}$; they support this by a study of the change of the refractive index.

Viscosity

For the viscosity, η , Chapman and Larson (1963) give for a tektite of 76% SiO_2 , converted to S.I. units,

$$\log \eta = \frac{27,620}{T - 262} - 10.09 \text{ N}\cdot\text{s}\cdot\text{m}^{-2}$$

5.13

where T is the absolute temperature. (One $\text{N}\cdot\text{s}\cdot\text{m}^{-2}$ is 10 poise).

This is somewhat lower than the measurements of Volarovich and Leontieva (1939) (See Fig. 5-6). Friedman (1963) reports two measurements on a bediasite, plotted on Fig. 5-7.

Hoyte et al (1965) find that the activation energy for viscosity, E_{η} , is 3.65 times that for electrical resistivity, E_{ρ} . By measuring resistivity from $330^{\circ} - 450^{\circ}\text{K}$, they were able to construct viscosity curves from $1370^{\circ} - 1770^{\circ}\text{K}$. From their work they concluded that the following formula represents the viscosity, η :

$$\ln \eta = \ln \psi' + rE_{\rho}/RT$$

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where $\ln \psi'$ is nearly constant for all tektites, $r = 3.65$,

R is the gas constant, and T is the Kelvin temperature. Numerically

$$\log_{10} \eta = -5.62 + \frac{51.6E_{\eta}}{T} \quad (\text{N} \cdot \text{s} \cdot \text{m}^{-2})$$

5.14

where E_{η} is the activation energy for viscosity in kJ mol^{-1} .

From the chart of Hoyte et al, it is clear that E_{η} varies linearly

with SiO_2 content, being about 277 kJ mol^{-1} ($66.4 \text{ kcal mol}^{-1}$)

for 70% SiO_2 and about 335 kJ mol^{-1} (80 kcal mol^{-1}) for 80% SiO_2 .

Note that their equation 11 is in error; the coefficient of $1/T$

should be 10^3 times larger.

Hoyte et al point out that E_{η} is about 7.5 kJ mol^{-1} ($1.8 \text{ kcal mol}^{-1}$) higher for annealed glass than for quenched glass.

Tektites are to be regarded as quenched. The discrepancy between their values and Chapman's is approximately equal to the difference between annealed glass and quenched glass (Fig. 5-7).

The viscosity of Libyan Desert glass was found by Friedman and Parker (1969) to be almost 6 orders of magnitude higher than that of australite glass at the same temperature. The activation energy is about 460 kJ mol^{-1} ($110 \text{ kcal mol}^{-1}$).

Specific heat

The specific heat of tektite glass was found by Chapman and Larson (1963) for a Port Campbell australite with 76% SiO_2 to be

$$C_p = 0.953 + 0.00025 T - \frac{27,000}{T^2} \quad (\text{kJ kg}^{-1} \text{ } ^\circ\text{K}^{-1})$$

Thermal conductivity

The thermal conductivity (Chapman and Larson, 1963) for the same kind of tektite as above was found to be

$$k = 0.001695 - \frac{0.19}{T} (\text{kJm}^{-1} \text{ } ^\circ\text{K}^{-1} \text{ s}^{-1})$$

Time of cooling

Adams and Spreurer (1967) calculated the cooling time for an opaque sphere in space, radiating to a vacuum, and having internal heat transfer by conduction. The value of the thermal conductivity which they adopted was about 1/4 of that given above, so that allowance must be made in applying their graphs to the tektite problem. This correction was made by Centolanzi (1969). Earlier studies of the same problem were made by Watson (1935) and Lovering (1962).

Vapor pressure

The vapor pressure of tektite glass was found by Chapman and Larson (1963) from mass-loss measurements as

$$\ln P_v = \frac{-57,800}{T} + 24.1$$

where P_v is in newton/meter² and T in degrees Kelvin.

Walter and Carron (1964) attempted to measure the vapor pressure by determining the boiling point of silica glass as a function of temperature. They found vapor pressures which, at the lower end of their range, near 1500°C, were approximately 10⁶ times higher than those of Chapman and Scheiber. This work was criticized by Centolanzi and Chapman (1966) who redetermined

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5.15

5.16

lm
5.17

PHYSICAL PROPERTIES OF TEKTITES

the vapor pressure by a number of different methods, all of which led to the result that the vapor pressure is very nearly that given by Chapman and Scheiber, being

$$\ln P_v = \frac{-57,400}{T} + 23.50 \quad (\text{Nm}^{-2})$$

5.19

The results of Walter and Carron(1964) were apparently caused by the fact that tektite glass contains a small amount of volatile material, which forms bubbles at a temperature much lower than the boiling point of the majority of tektite material. The work of Walter and Carron is valuable for questions involving escape of volatiles; but for determinations of vapor pressure, as this is needed for e.g.ablation calculations, the data to use is that of Centolanzi and Chapman (1966).

Heat of vaporization

From their thermal data, Centolanzi and Chapman (1966) determined a heat of vaporization of 11,900 kJ kg⁻¹, using the Clausius-Clapeyron relation.

Diffusion coefficients

The diffusion of gases in tektite glass was studied by Reynolds (1960); he found that helium should diffuse out of a typical tektite in five years; neon requires about a million years; other gases, apart from hydrogen, require times much longer than available. In accordance with these predictions, O'Keefe et al

(1962, 1964) found He, and Ne, but not Ar or N in tektite vesicles.

The diffusion of metals in tektite glass was studied by Varshneya and Cooper (1969) and Varshneya (1970). They were concerned with what is called the effective binary diffusion coefficient. Their data yield the results shown in Fig. 5-8. At 1800°C , the effective binary diffusion coefficient for iron in tektite glass is about $10^{-11} \text{ m}^2 \text{ s}^{-1}$; that for silicon is about 1/3 as large. These results are of significance in studies of the rate of homogenization of tektite glass.

Thermal variation of magnetic susceptibility

Thorpe and Senftle (1964) studied the variation of the magnetic susceptibility of tektites with temperature. In addition to the variation to be expected if the susceptibility is due to ferrous iron, they found a temperature-independent component, which they attributed to the presence of about 30 ppm of free iron or Fe_2O_3 in the form of submicroscopic spherules. They attribute the brown color characteristic of tektites to the same spherules.

Thermoluminescence

Durrani et al (1970) and Durrani (1971a) have studied tektite thermoluminescence. The phenomena are complex, and investigation has only begun. An age (since last heating) of $0.7^{+.24}_{-.19}$ m.y. has been found for indochinites.

THE CHEMICAL COMPOSITION OF TEKTITES

RELIABILITY OF ANALYSES

Barnes (1939) compiled the tektite analyses available up to that time. Of these, the analyses prior to 1930 are not generally useful; many even lack TiO_2 . Of the analyses made in the 1930's the two bediasite analyses reported by Barnes (1939) are to be rejected; the MgO/CaO ratio in them is highly discordant with all other analyses. The analyses of Raoult, reported by Lacroix in various papers of this period, are comparable with good modern wet-chemical analyses.

In most wet-chemical analyses, there is a tendency to overstate the content of water and ferric iron. Friedman (1958) and Gilchrist et al (1969) showed that water is present at the level of 0.01% (or less); it is thus below the limit of detection by wet-chemical methods. The ferric-ferrous ratio was found to be 0.05 for bediasites by Thorpe et al (1963); values much over 0.15 are rare in modern analyses.

With respect to trace elements, the work of Cohen (1959) on lithium and rubidium has been criticized by Schnetzler and Pinson (1963). The value of 7700 ppm for barium in moldavites is startling and very important if correct (Vorob'yev, 1960a); unfortunately

accompanying values for barium in indochinites (Vorob'yev, 1959b) exceed those of other workers by a considerable factor.

CENTRAL COMPOSITION

Table 6-1 gives the chemical composition of a representative tektite, in particular an australite. For most elements, it is taken from S. R. Taylor (1966), australite No. 28, 11947D. This australite is closely similar to the normal australite of Chapman and Scheiber (1969b), No. 45, AN 99. Where Taylor does not have data, the gaps have been filled with other australite analyses as shown in the notes, or, in one or two cases of non-critical elements, with other kinds of tektites.

In Fig. 6-1 and 6-2, the composition is compared respectively with that of the USGS standard granite, G-1, and the standard basalt, W-1, using the 1972 recommended values (Flanagan, 1973). (These rocks are not necessarily representative; they are chemical standards, which are useful here because they have been fully and carefully analyzed, and because they give an adequate idea of the two principal rock types). The arrangement is the long form of the periodic table. The ratio of the element concentration, in grams per gram, to the concentration of the standard, is represented logarithmically by bars going upward for excesses,

and downward for deficiencies.

It is seen that, particularly on the left side of the periodic table, the tektite central composition falls between the granite and the basalt; where the bars are upward in the granite, they are downward in the basalt, and vice versa. Exceptions are the volatile elements; hydrogen, and a large group on the right side of the table, enclosed by a line. For these elements, tektites are deficient as compared with both standard rocks.

It is therefore logical to compare with an intermediate rock; Fig. 6-3 shows the comparison with the standard andesite, AGV-1 (Flanagan, 1973); it is obvious that this is a better match than either the basalt or the granite, but the deficiencies on the right side of the table remain conspicuous.

This result is surprising, in a way, because the SiO_2 content is 70.4% for the central tektite, and 72.6% for G-1, while for AGV-1 it is 59.0%. We might thus have expected the tektite to be closer to the granite than to the andesite, because it is well-known that the chemical composition of igneous rocks is largely determined by the silica content. However, it was pointed out by F.P. Mueller (1915) that tektites could be distinguished from terrestrial igneous rocks because the ratio $(\text{FeO} + \text{MgO}) / (\text{Na}_2\text{O} + \text{K}_2\text{O})$ was higher for a given silica content. This ratio decreases with increasing

silica content, so that Mueller was finding the above-mentioned result, namely that tektite composition resembles (for most elements) that of terrestrial rocks of lower silica content. (We refer here to the left side of the periodic table). F.E. Suess (1933) comments similarly; so does Loewinson-Lessing (1935). Barnes (1939) used this fact as the basis for his conclusion that tektites are for the most part formed from terrestrial sedimentary rocks. Urey (1958a, 1958b) commented similarly. The same idea was expressed by Cherry and his collaborators (Cherry et al, 1960, S.R. Taylor, 1960, Cherry and Taylor, 1961, S.R. Taylor and Sachs, 1961, S.R. Taylor et al, 1961, S.R. Taylor, 1962c).

Later, Taylor suggested that the mixing process should not be understood literally; he pointed out that sedimentary processes could enhance the silica content in the way required. In particular, Taylor studied the Henbury sandstone (see Fig. 6-4); here it is clear that sedimentary processes are enhancing the silica content, because some of the sandstone has as much as 94% SiO_2 (S.R. Taylor and Kolbe, 1965). By proper choice of sandstone, Taylor was able to come close to the australite composition, both in silica content and in other non-volatile elements (S.R. Taylor, 1966).

The discrepancy in hydrogen (i.e. water content) was commented on by F.E. Suess (1900, p. 247); in fact, the field test

to distinguish a tektite from an obsidian is to heat it with a blowtorch or blowpipe; the tektite melts with at most a few bubbles, while the obsidian foams (La Paz, 1948). Terrestrial igneous rocks tend to have about 5000 ppm water, and sedimentary rocks several times as much. In an impact, however, the water may escape, at the price of turning the rock into a mass of bubbles (see e.g. S.R. Taylor and Kolbe, 1965).

On the right side of the periodic table, there are major discrepancies in many of the elements which are volatile at temperatures of the order of 1000°C . These discrepancies are difficult to measure by the usual methods of spectrochemical analysis. The elements are scarce; they volatilize at temperatures below those which are optimum for the metals on the left side of the diagram; and their spectra often have the important lines in relatively inaccessible parts of the ultraviolet. Hence these discrepancies tend to be overlooked. Nevertheless Preuss (1935) and Heide (1936b) noted that tektites are lower in Cu, Ge, Sn, and Pb than their suggested terrestrial comparison material (Norwegian loam); similarly S.R. Taylor (1966) remarked on the deficiencies in Cu, Pb, Sn, Tl, In, Bi compared with the Henbury impact glasses.

Similar discrepancies are conspicuous when lunar rocks are compared with terrestrial rocks of similar type. In Fig. 6-5

a basaltic clast, 14321.223 from Apollo 14 (Wänke et al, 1972), is compared with W-1. In Fig. 6-6 the central tektite composition is compared with lunar sample 12013, the only lunar sample of acidic composition for which substantial trace element data exist. The comparison is unsatisfactory in several respects; but it suggests that the systematic discrepancy in the volatile elements is removed.

There is also a marked difference in the ratio of ferrous to ferric iron, which does not appear on the charts. Terrestrial acid igneous rocks or terrestrial sandstones typically have ferric-ferrous ratios of the order of 1, or even more. For tektites, as mentioned, the ratio is generally less than 0.15.

The chemical parameter which underlies the ferric-ferrous ratio is the oxygen fugacity, which is numerically equal to the equilibrium partial pressure of oxygen, P_{O_2} , that is, to the value of the partial pressure which would be in equilibrium with the glass at the given temperature. Walter and Doan (1969) report preliminary values as follows:

$$\log_{10} P_{O_2} = 9.13 - 32,600 / T$$

where P_{O_2} is in atmospheres, and T is the Kelvin temperature. The equivalent pressure in $N \cdot m^{-2}$ is greater by a factor 10^5 . The relation yields $10^{-9.6} N \cdot m^{-2}$ (or $10^{-14.6}$ atmospheres) at $1100^\circ C$, about 6 orders of magnitude below terrestrial rocks at this temperature. (Walter and Doan's value of $10^{-17.6}$ atmospheres

for 800°C is a slip; it should be about $10^{-21.3}$ according to their unpublished charts). More measurements are needed. , 44

Vorob'yev (1959a) found magnetite spherules, often hollow, in surface cavities of Philippine tektites. Kleinman (1967) found magnetite inclusions some of which had nickel-free iron cores, as if the tektites had formed in equilibrium with metallic iron, which later oxidized (verbal suggestion by L.S. Walter). This would again suggest a low oxygen fugacity.

Brett (1967) has noted a relation between the nickel content of metallic spherules in tektites and impact glasses, and the presence or absence of a halo of iron oxide in the surrounding glass. It appears that for impact glasses, a portion of the iron oxidizes and dissolves in the glass, leaving the spherule nickel-rich. For tektites, on the other hand, the nickel enrichment and the iron oxide halo are both missing. This result seems to imply that the oxygen fugacity in tektites is much lower than in impact glasses, so that they do not tend to oxidize the iron.

THE PRINCIPAL FAMILIES OF TEKTITES

When one is confronted with a hand specimen of a tektite, it is usually possible to find out where it has come from by analyzing it. Most tektite analyses are carried out in weight percent of major oxides. By comparison with the central composition

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(Table 6-1), the North American tektites (Table 6-2, cols. 15-19) are systematically low in CaO and MgO. Moldavites tend to have high silica (over 75%) and high K_2O (over 2.5%). Ivory Coast tektites usually have low silica (under 70%) and often have $Na_2O > K_2O$. Although Aouelloul glass is broadly similar to Darwin glass, both being in the range near 85% SiO_2 , the Aouelloul glass has higher CaO and MgO.

When careful studies are made, including microtektites and rare types of macrotektites, it is seen that the range within one strewn field is often much greater than the range from one strewn field to another. Fig. 6-7 diagrams the more important types of tektites within the Australasian strewn field. To construct the figure, the weight percent MgO was taken from the analysis, added to CaO and 0.05 SiO_2 ; call the sum s . Then s/MgO is plotted vertically upward from the base of the triangle, and similarly for the other two directions. The central composition of Table 1 is that of the normal australite, No. 1, near the middle of Fig. 6-7. Normal philippinites (10) and normal indochinites (2) are nearby.

The principal variations in tektite composition are toward high magnesium content (bottle-green microtektites, 6 and 7), and toward high silica Darwin glass (3 and 4).

There is also a less common class of high-calcium tektites (11).

An important class of microtektites lies on a spur pointing away from the SiO_2 vertex (8). The curious class of the low-calcium, high-aluminum tektites (5) is interesting because the nickel-iron spherules (Chao et al, 1962, 1964) occur in tektites of this composition. Even in Aouelloul glass (Chapman and Scheiber, 1969, Chao et al, 1966a), which is so different from most of the philippinites and indochinites where most of these spherules have been found, there is a narrow zone of glass of similar composition (O'Keefe et al, 1971a).

The high Na/K tektites (Chapman and Scheiber, 1969) are of interest because their major-element analyses resemble terrestrial andesites (apart from the usual lack of water and ferric iron). They resemble Ivory Coast tektites in composition, and their dating is a major puzzle (Chapter 7).

Fig. 6-8 represents the other tektite strewn fields just as Fig. 6-7 presents the Australasian. Note that the North American tektites lie near the SiO_2 vertex, not because they are silica-rich but because they are poor in CaO and MgO.

TRENDS IN COMPOSITION

Correlations with silica content

The first-order description of chemical trends in tektites

is that silica is negatively correlated with other oxides. Variation diagrams (plots of oxide concentration versus silica concentration) were prepared by Suess (1900, p. 236), Summers (¹⁹¹³~~1901~~), Suess (1914), Barnes (1939, figs. 93, 94) and Cassidy (1958). Cherry and Taylor (1959) sought to explain the correlation by assuming a mix of arkosic sandstone with a hypothetical cometary composition resembling the silicate portion of a chondritic meteorite. This idea became untenable (S. R. Taylor et al, 1961) when more refined analysis showed that magnesium in tektites is positively correlated with alkalis such as Na_2O ; it was replaced by the hypothesis that tektites are a mixture of shale plus pure quartz in varying proportions.

Lowman (1962), using Barnes's (1939) compilation, compared the variance of tektite compositions with those of randomly chosen igneous and sedimentary rocks in the same range of silica content; the tektites were markedly narrower in range, especially by comparison with sedimentary rocks. Cuttitta et al (1963a,b) and Chao (1963b) also noted the positive correlation of the alkali elements with one another, and the general negative correlation of oxides with SiO_2 ; they found Al_2O_3 in indochinites to show no correlation. Tatlock (1966) and Meadows et al (1967) showed that the variances become even narrower when modern analyses are used. As noted above, Taylor and his coworkers later attributed the correlation

with silica to sedimentary differentiation (quartz grains enriched relative to weaker materials) rather than to a mixing process in the literal sense.

The K/Rb ratio was studied by Ahrens et al (1952), S.R. Taylor (1960), Pinson et al (1965), S.R. Taylor et al (1967); values converged toward 175-195. These resemble the ratios in terrestrial rocks, and do not support the hypothesis of Ehmann and Kohman (1958b, Kohman, 1959) that tektites come from outside the solar system.

Similarly Setser and Ehmann (1964) found a value near 30 for Zr/Hf in tektites, as in some sediments. Greenland and Lovering (1965) found a tight positive correlation of MnO with FeO.

Ehmann and Showalter (1971) found that Na is positively correlated with Fe in australites, although the correlation is negative in subgraywackes. Rybach and Adams (1969a,b) found that the Th/U ratio is 2.6 for Ivory Coast tektites, but is considerably greater than 4 (the cosmic value) for other tektites. For K/U they found 13,000, similar to terrestrial values.

The question whether these correlations are simply the result of the variation of silica was attacked by Leake (1970) and Walter and Shadid (1970) using Niggli values. Both papers

concluded that the compositional trends do not match any of the proposed theories (igneous differentiation, sedimentary differentiation, differential volatilization).

Some light is shed on these relations by the findings of Glass (1970a) and Walter (unpublished manuscript kindly communicated) to the effect that compositional trends among tektites are matched by compositional trends within individual tektites, as if the tektites were in some sense composites of microtektites (see Chapter 4).

Correlations with nickel, chromium and magnesium

All of the above are more or less explicable in terms of a mixing model having silica as one end member, and a rock of intermediate acidity as the other. But in some groups of tektites, there is the appearance of a different kind of mixing relation, in which the basic end-member is an ultrabasic rock, conceivably like a bottle-green microtektite, and the acidic end-member is something like a moldavite.

The first evidence for the ultrabasic end-member seems to have been the findings of Preuss (1934) that chromium and nickel are enhanced by a factor 10 in billitonites as compared with australites. He noted that although nickel enhancement occurs in impact glasses, there is no enhancement of chromium as in

tektites. He discussed the matter further in his great spectrochemical study (Preuss, 1935); Heide also referred to it (1936b); later (1938b), Heide mentioned that the nickel-rich and chromium-rich tektites are distributed along a line from Billiton through Borneo, Cambodia, Cochin-China, with nickel-poor tektites on both sides. S.R. Taylor (1962b) and Schnetzler and Pinson (1963) reiterated Preuss's argument, namely that the simultaneous enhancement of chromium and nickel cannot be due to meteoritic contamination.

Chao (1963b) showed that nickel plus chromium is weakly correlated with MgO plus FeO in bediasites, but strongly correlated in australites. S.R. Taylor (1964) noted two australites enriched in nickel, chromium and cobalt. Pinson and Griswold (1969) and Ehmann and Showalter (1971) again commented on the nickel-chromium relation.

The subject was illuminated by Chapman and Scheiber (1969) who identified an important class of tektites in the Australasian strewn field, namely the high-magnesium tektites, which are enriched in magnesium, nickel, cobalt, and chromium. As Chapman and Scheiber remark, and as was later shown by Glass (1972b), the high-magnesium tektites agree in composition with the bottle-green microtektites in the range from 63% to 75% SiO_2 .

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Apparently the nickel-rich tektites of Heide and Preuss are the same as the high-magnesium family of Chapman and Scheiber. Unfortunately, owing to the very small amount of material available, there is no direct demonstration that the bottle-green microtektites are in fact nickel-rich; that they are chromium-rich was found by Glass (1972b).

High copper and boron in tektites

Chapman and Scheiber (1969b) found that many Muong-Nong tektites are enriched in Cu, B, and Pb. This discovery was confirmed and extended by Müller and Gentner (1973), who also found enrichments of Zn, Cl, and Br. The latter authors compare the enrichment to that observed in the orange soil of Apollo 17. The enrichments in Cl and Br are by factors of around 20; for Cu and B the factor is more like 5.

PETROGENETIC THEORIES

Volatilization

Cohen (1960b, c) deduced from the gallium-germanium ratio in tektites as compared with terrestrial glasses, that tektites had suffered severe differential volatilization. His measurements were questioned by S.R. Taylor and Sachs (1960) and Schnetzler and Pinson (1963). S.R. Taylor (1961) measured the distillation of alkali elements during ablation by comparing flanges and cores of australites;

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he found losses of alkali elements of about 20% for sodium and 5% to 10% for the other alkalis. Greenland and Lovering (1962, 1963) studied the relation of tektite compositions to those of granites and shales; they found that tektite compositions were derivable from granites, but not from shales. S.R. Taylor and Kolbe (1965) found little difference, even in volatile oxides other than CO_2 and water, between Henbury subgraywacke and the impact glass derived from it.

In a series of papers, Walter and coworkers (Walter, 1967, Walter and Giutronich, 1967, Walter and Adams, 1967, Walter and Shadid, 1970) have put forward the suggestion that the sequence of tektite compositions represents progressive volatilization, starting from a composition like that of the more silicic Muong Nong tektites (82% silica). The key point in these papers is the discovery that, in an oxygen-rich atmosphere, silica is a relatively volatile oxide, exceeded in volatility only by potash.

Walter's suggestion was criticized by Chapman and Scheiber (1969b). They referred to the above-mentioned results of Taylor and Kolbe (1965). They further argued that surface volatilization would not change the bulk composition, while volume ebullition (boiling) would produce a pumice, which is not observed. Diffusion in the available time is much too slow. Chapman and Scheiber further noticed that some Muong Nong tektites could not ever

have been strongly heated (they have irregular voids, which would have become round or ellipsoidal if melting had occurred) yet are near the low-silica end of the normal tektite sequence. They also found that copper volatilizes so readily that 90% will be lost before 1% of the total mass. It follows that tektites which contain copper in normal amounts cannot have suffered severe losses of total material. Finally, the trend of the relation of Mg and Ca to Al is at right angles to the trend to be expected for differential volatilization.

It is clear from Figs. 6-1 to 6-6 that differential volatilization has played a role in the history of tektite material at some time. The issue is between

a. Walter's idea that the loss of volatiles occurred at a very late stage, during a violent heating event occurring in an oxidizing atmosphere such as the earth's; and

b. An early volatilization, giving rise to the possibility that tektite composition can be used to make inferences about conditions in the region where they were formed (e.g. the deep interior of the moon).

The evidence at present seems to be against the first hypothesis.

Magmatic differentiation vs. sedimentary differentiation

Chapman and Scheiber (1969b) considered the possibility that the major element composition of tektites may result from

magmatic differentiation under conditions of total pressure which are less than those for parallel terrestrial rocks. They note that the alkali basalts seem to come from deeper in the earth than the tholeiitic basalts; they regard some tektite compositions as a natural extension of this distinction. In particular, they suggest that the higher silica content of tektites (as compared with terrestrial acid igneous rocks) and their lower content of alkali elements and other elements with large ionic radii is the result of magmatic differentiation at low pressure. (They are thinking of the lunar interior, where the maximum pressure, at the center, is 47 kilobars).

Chapman and Scheiber reject a sedimentary origin for tektites on the ground first pointed out by Lowman (1962) and later by Chao (1963b) and Tatlock (1965), that tektites show a much narrower field of composition than sedimentary rocks; and any given tektite family shows much less compositional range than a group of sandstones.

Tektites and achondrites

Tektites were compared with achondrites by Cassidy (1958) who noted that, as compared with generally similar rocks, both tektites and achondrites tended to be more silicic. Kvasha and Gorshkov (1961) made the same point, adding that both tektites and achondrites are relatively deficient in alkalis. Morgan (1969)

noted that the correlation line between U and Th in basaltic achondrites would approach the figure for tektites.

A direct connection of tektites with the parent body of the achondrites does not seem plausible at present; but it is important to remember that the basaltic achondrites resemble lunar basalts in their chemical composition. The affinities noted may actually be telling us something about processes of magmatic evolution on a body of low gravity and low water content.

GASES IN TEKTITES

Beck (1910) cited work by Brun to the effect that when tektites are heated, the principal gases given off were CO_2 and CO in roughly equal amounts, H_2 , SO_2 , and traces of N_2 . Döring and Stutzer (1928) found similar proportions; both analyses were very different from those for obsidians.

H.E. Suess (1951) agreed generally with Brun (as cited by Beck) on the gas content of the rock; it is 0.1 to $0.3 \text{ cm}^3 \text{ g}^{-1}$; Suess found chiefly CO, with some CO_2 and H_2 ; he also found considerable amounts of water, especially in an australite. The carbon found corresponds to about $50 - 150 \text{ ppm C}$ in the tektite, and is thus of the order of the values given by Muenow et al (1971) and Dolgov et al (1969a,b) for organic compounds in tektites.

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In the vesicles, Suess (1951) found less than 10^{-3} atmospheres. O'Keefe et al (1962) identified Ne, He, O, and O₂ in a large vesicle of a bediasite using an electrodeless discharge. The Ne and He appeared to be at about the same level as in the atmosphere, and had probably diffused in. Zähringer (1963b) confirmed the finding of Ne and He in nearly empty vesicles. In other vesicles, Zähringer found N₂ and argon in their atmospheric ratio to one another. The work was extended by Müller and Gentner (1970) and by Jessburger and Gentner (1972). These workers found N₂, Ar, Kr, and Xe in the same relative proportions as in the atmosphere, and with the same isotopic abundances as in the atmosphere. They do not feel that these vesicles have been filled by leakage from the atmosphere, because the CO₂ is a major component, and O₂ is greatly impoverished as compared with the atmosphere. On the other hand, we may note that in the soil, the air ("soil air") is depleted in O₂ and enriched in CO₂. Since the tektites had been above ground for a considerable time before they were studied, and since they were outgassed in vacuum for several days before they were crushed, it is necessary to suppose either that the leaks were very slow, or that they had actually become stopped up in the course of time.

Gentner and Jessburger also find CO; this, they feel, rules out soil air. On the other hand, it might have been a true initial

constituent of the gases, as reported by the early workers. The gaseous mix which Jessburger and Gentner report, with CO_2 greatly in excess of CO , and with minor quantities of free oxygen, would not be in equilibrium with tektite glass. It is hard to believe that it was ever in contact with tektite glass at high temperatures.

COMPARISONS OF COMPOSITIONS WITH IMPACT MATERIALS

Ries crater glass vs moldavites

Cohen (1961a) suggested that the moldavites originated from the Ries Kessel, a large impact crater in S. Germany. On the basis of chemical comparisons, Chao (1963b), von Engelhardt and Hörz (1965), Preuss and Sassenscheidt (1966), von Engelhardt (1967), and Barnes (1969a) have all concluded that the moldavites cannot be derived from Ries impact glass, including certain small dense pieces of unusual homogeneity. A chemical comparison is given by Chao (1963b); Table 6-4 from von Engelhardt (1967) compares a suevite (Ries impact glass) with moldavite composition.

A number of investigators have suggested that although the moldavites cannot be connected chemically with the impact glasses, which in turn are related to basement rocks, they may be related to mixes of Mesozoic sediments (Preuss and Sassenscheidt, 1966, Preuss, 1967, Bouska et al, 1973). Preuss had difficulty explaining

the comparative abundance of CaO in this way. Bouska et al further explored the trace-element composition of the local claystones and sandstones, without success. A convincing source material for the moldavites has not been found.

Bosumtwi crater glass vs Ivory Coast tektites.

Cohen (1963) suggested that the Ivory Coast tektites are the product of an impact at the Bosumtwi crater, in Ghana, at $6^{\circ}32'$ N latitude, $1^{\circ}23'$ W longitude (O'Connell, 1965). From the chemical standpoint the best evidence is as shown in Table 6-5. Clearly the white glass listed in Table 6-5 has nothing to do with the Ivory Coast tektites. From MgO and Na₂O, Cu, Rb, Li, Mn, Cr, Co, and Ni it appears that the gray glass is not like the tektites. With respect to the green and black glasses, the case for similarity is stronger; here the Student t-test has been applied; the probability of no better agreement is shown in the last column of the table.

If the differences were due to accidental errors of measurement, or to random variations from sample to sample, we would expect that the calculated probabilities of no better agreement would range uniformly from 0 to 1. For instance, out of 30 trials, we would expect that the probability of no better agreement would turn out to be less than 0.033 (1/30) once; less than 0.10 three times, and so on. A distribution of this kind is in fact observed when the

Henbury subgraywacke is compared with the Henbury impact glass. But for the comparison of Bosumtwi glass with the Ivory Coast tektites, the distribution is entirely different; the values of P cluster around zero. It follows that the Ivory Coast tektites cannot be regarded as related to the Bosumtwi glass in the same way that the Henbury glass is related to Henbury subgraywacke; i.e. if the Ivory Coast tektites are from Bosumtwi then we have not identified the source material.

There is, however, a remarkable chemical resemblance between the two, as shown in Fig. 6-9. In particular, Ivory Coast tektites are different from other tektites in the rare earth pattern; the heavy rare earths are slightly lower relative to most tektites. The Bosumtwi glass is like the Ivory Coast tektites in rare earth pattern (Schnetzler et al, 1967a). The tektite Th/U ration is 2.9, instead of the 5 or 6 generally found in tektites; and the Bosumtwi rock (not specifically the glass) is similar (Rybach and Adams, 1969a, b).

The ferric-ferrous ratio in the Bosumtwi glass is 0.2 and 0.4 for the green and black glasses respectively; for the white and gray Bosumtwi glasses it is 2.8 and 1.7; for the tektites it is usually less than 0.1 and in all cases less than 0.15. The water content of the Bosumtwi glasses is 0.4 to 3.7 %;

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for the tektites it was not included, yet the mean sum is 99.96% (incorrectly given as 100.03%) which indicates an unmeasurable water content.

No chemical analyses of the Bosumtwi rocks have been reported which resemble the bottle-green microtektites of the Ivory Coast strewn field.

In conclusion it appears that the Bosumtwi white and gray glasses have no apparent relation to the Ivory Coast tektites.

The black and green glasses show some striking resemblances to Ivory Coast tektites, but there are also serious discrepancies. It is clear that the two rocks are not chemically identical, but the degree of chemical similarity is surprising, and much closer than in the case of the Ries and the moldavites.

Aouelloul crater glass vs local (Zli) sandstone.

Mono^d (1952), on the basis of analyses by Campbell-Smith and Hey (1952a,b), believed that the Aouelloul crater glass was chemically so different from the local Ordovician sandstones (Oujeft, and overlying Zli) that the glass could not come from the sandstone. Chao et al (1966b) analyzed specimens of Zli which bore a much closer resemblance to Aouelloul glass. Discrepancies remained, however, not only in ferric/ferrous ratio and water content, but in total Fe and in CaO. Chao et al suggested that the Fe

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discrepancy might be due to an impacting iron meteorite. They noted, without giving data, that there were also serious discrepancies in the trace elements Ni, Co, Cr, V, Cu, Sc. Nickel was not detected in the sandstone, but was at the level of 330-440 ppm in the glass.

O'Keefe and Annell (unpublished, 1974) noted that the application of the Student t-test indicated highly significant differences between the sandstone and the glass in the major elements. The 2% Fe, which must be added to make up the iron deficiency, should call for at least 1000 ppm Ni if the extra iron is due to an impacting meteorite; the actual amount is 330-430 (Chao et al, 1966b).

Here as at Bosumtwi it is clear that investigations up to this point have not turned up any rock which could be the source of the Aouelloul glass, in the sense that the Henbury subgraywacke is the source of Henbury glass. The failure is much more significant than at Bosumtwi, because the crater is only some 300 meters in diameter, versus 10 kilometers at Bosumtwi; the volume of rock disturbed is perhaps 40,000 times less. The strata at Aouelloul are horizontal, and the Zli is at the top -- in fact it is eroded away over most of the surrounding area. The whole thickness of the Zli was sampled by Fudali; and the analysis of his suite of specimens would do much to settle the question.

COMPARISONS WITH LUNAR ROCKS

12013 compared with the high-magnesium tektites

O'Keefe (1970a), Mason and Melson (1970, p. 115) and Chapman (1971) have drawn attention to the resemblance of lunar sample 12013 to certain high-magnesium tektites. The resemblance in the major elements is striking; however, when the minor and trace elements are considered, the discordances are large, particularly in Ba, Cr, Y, Zr (Chapman, 1971), also the rare earth elements Hf, Th, U (Showalter et al, 1971).

Rock 12013 is inhomogeneous; there is a dark portion, which resembles the lunar rock called KREEP, and a lighter more acidic portion. Chapman (1971) draws attention to the fact that the compositional trends observed in 12013 parallel those observed among the high-magnesium tektites. See Figs. 6-10, 6-11, 6-12. It may be significant that in both cases the compositional trends suggest mixing rather than a liquid line of descent.

Glass (1972b) finds that the bottle-green microtektites (which presumably continue the high-magnesium series toward lower silica content) have Cr_2O_3 up to about 0.2%, implying Cr up to 0.14%; this bridges most of the gap between 12013 and the high-magnesium tektites. Other trace elements data on the bottle-green microtektites is not available.

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Lunar soil particles

Studies of lunar soil particles (Reid et al, 1972a,b, Glass et al, 1972) show that a component is present in the lunar soils at the level of about 2 to 5 particles per thousand of a type which is often called granitic. Much of the material is more potassic than any tektite (Table 6-6), but some will bear comparison with a high-calcium tektite. There are very few analyses of this material.

It should be kept in mind that all known tektites have survived on earth for a period of at least several hundred thousand years. It is known that the durability of glass decreases with increasing content of potassium; caution is called for in drawing inferences from the lack of potassium-rich tektites.

Libyan Desert glass and lunar tridymite and cristobalite

Libyan Desert glass has a superficial chemical resemblance to a sandstone of the very common type called quartz arenite (Pettijohn et al, 1972) and earlier called orthoquartzite. Quartz arenite is defined as having 95% quartz or more. However, as can be seen from Table 6-7, the relative proportions of oxides other than silica are strikingly different. For the quartz arenites they tend to resemble the relative abundances found in acid igneous rocks, or else to consist largely of the iron oxide which often cements the

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sand grains.

For Libyan Desert glass, on the other hand, TiO_2 is almost half as abundant as Al_2O_3 ; CaO is about 10 times as high as MgO ; and Na_2O ten times as high as K_2O .

Futrell has pointed out in an unpublished note kindly communicated that the same relations are observed in lunar tridymites (see Table 6-7). The proceedings of the Lunar Science Conferences have numerous analyses of lunar tridymites and cristobalites; it is found that the relations shown in Table 6-7 are very common, although not universal.

In the course of his expedition to the region of the Libyan Desert glass, Barnes recovered a sample of the underlying quartz arenite (the Nubian sandstone). It is seen (Table 6-7) to bear little resemblance to the Libyan Desert glass except in silica content.

Bottle-green microtektites and mesosiderites

The bottle-green microtektites resemble to some extent the silicate portions of mesosiderites (meteorites which are mixtures of stone and metal, with the stone predominating). Duke and Silver (1967) suggested that the silicate portion of the mesosiderite Estherville might be a model for the parent material of two other meteorite types, namely eucrites and howardites. Since eucrites resemble lunar mare rocks, and howardites resemble (chemically

only) certain green lunar glass spherules, it is of special interest to compare the silicate portions of Estherville with bottle-green microtektites. The comparison in Table 6-8 is with the average Ivory Coast bottle-green microtektite. 165

Note the higher Al_2O_3 content of the bottle-green microtektites. The significance of the relation noted here is not necessarily that bottle-green microtektites and mesosiderites come from the same place as that the two rocks both represent (imperfectly) some kind of primitive composition such as might be expected in the deep interior of a planet.

SUMMARY

Among terrestrial rocks, the intermediate igneous rocks and the sandstones resemble tektites most. Sandstones have a slight advantage, because they can combine a high silica content with enrichment of the femic components. Tektites differ systematically from terrestrial rocks in their low water content, low ferric-ferrous ratio, and low abundances of the volatile elements; in these respects tektites resemble lunar rocks.

Specific chemical comparisons of tektites with impactites from terrestrial meteorite craters are not encouraging except in the case of the comparison between the Bosumtwi crater in Ghana

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and the Ivory Coast tektites; here, although chemical identity does not exist, there is a remarkably close resemblance in several respects.

Few comparisons have been made between tektites and lunar rocks. There are resemblances in major elements between lunar specimen 12013 and the high-magnesium tektites; between some lunar soil particles and some microtektites; and between Libyan Desert glass and lunar tridymite. Trace element analyses are available only for the comparison of 12013 with the javanites; the resemblance is not close.

It appears that the most interesting elements for many of these comparisons are the neglected volatile elements on the right side of the periodic table; it is hoped that these can be studied in the future.

CHAPTER 7

ISOTOPES, FISSION TRACKS AND COSMIC RAY TRACKS

INTRODUCTION

The most important application of isotopic analysis in the tektite problem to date has been the discovery of the ages of the strewn fields. Since fission-track analysis leads to similar (and, fortunately, concordant) results, the fission-track methods of age measurement are described together with the isotopic age measurements.

Isotopic analysis has also been used to test for effects of primary cosmic ray bombardment, such as is detected in meteorites. Here again the track methods reach the same result, and are described together with the isotopic methods.

Isotope studies of D/H, and the stable isotopes of oxygen and silicon are of importance in identifying possible source materials for tektites.

TEKTITE AGES

The amount (in numbers of atoms) of any radioactive parent nuclide P , after a time t is given by

$$P = P_0 e^{-\lambda t} \quad 7.1$$

where P_0 is the initial amount of the parent material, and λ is the

decay constant, which is related to the half-life $T_{1/2}$ by

$$T_{1/2} = - \frac{0.6931}{\lambda} \quad 7.2$$

The amount in numbers of atoms of any daughter product D is given by

$$D = D_0 + P_0 (1 - e^{-\lambda t}) \quad 7.3$$

where D_0 is the initial amount of the daughter product.

The reader is warned that in many discussions of radioactive processes, the equations are apt to be written so as to give the unknowns, P_0 and D_0 , from the known quantities; this is how the experimenter sees the problem. We are here chiefly interested in the results, and have therefore used this more obvious way of looking at the relations.

Potassium-argon method

The decay of ^{40}K to ^{40}Ar (by electron capture) gives a method of determining the age of a rock since the time when it was last thoroughly outgassed. In principle, one collects the argon by heating, allows for atmospheric argon (which contains ^{36}Ar ; the radiogenic Ar is pure ^{40}Ar), and compares with the total K, assuming that ^{40}K is 0.0118 percent, and using appropriate values for the decay constant and for the side production of (useless) ^{40}Ca .

The important point is the heating required to drive out the argon. Suess et al (1951) heated tektites to 400°C ; they obtained only upper limits to the ages. Gerling and Yaschenko (1952)

also obtained only upper limits, including a limit of 3.1 m.y. for the moldavites. Gentner and Zähringer (1959, 1960b) got values of 0.53 to 0.69 m.y. for the Australasian tektites, and 8.5 to 8.9 m.y. for moldavites. They commented that Gerling and Yaschenko probably had not heated the moldavites strongly enough; they recommended 15 minutes at 1800°C . Reynolds (1960) got ages up to 0.80 m.y. for the Australasian tektites, 13.5 m.y. for the moldavites, and around 30 m.y. for North American tektites; these results were substantially correct. Next, Gentner, Lippolt and Schaeffer (1961), referring to Lippolt's dissertation, raised the age of the moldavites to 14.7 m.y., in agreement with Reynolds and with their own values for the age of the impact glass from the Ries Kessel; it is clear that their earlier moldavite ages were themselves in error as a result of incomplete outgassing. The same authors recommend (1963) that the sample be evaporated. Signer (1963) found that he could not extract all the argon by heating for 6 hours at 1800°C ; he needed 20 hours at 1800° or 2 hours at 2000°C . He remarked that there is no conceivable way by which such outgassing could have occurred in space; K would have been lost with Ar at high temperatures. Schaeffer (1966) and McDougall and Lovering (1969) reiterate the need for complete vaporization to get out the argon. Schaeffer comments that the difficulty is connected with the lack of

volatiles in tektites; in the absence of volatiles, bubbles do not form.

In this case, as Signer remarks, gases must reach the surface by diffusion, which requires an inordinate amount of time.

The point is of considerable theoretical interest. Tektites normally yield ages which are concordant with each other and with the stratigraphic age of the materials in which they are found. It seems to follow that they were thoroughly outgassed near the time of their arrival at the earth. In the case of the Ries and Bosumtwi glasses, the outgassing might have occurred while the glass was buried in a hot deposit of throwout; argon will diffuse out of rocks at moderate temperatures if very long times are available. On the other hand, rocks which cool in flight are found to lose only part of their argon (Hartung, 1971); thus it is difficult to explain the argon loss for tektites if they are formed by meteorite impact on earth. Among known impact glasses, careful selection is required to find glasses which have been thoroughly outgassed.

Table 7-1 gives the K-Ar ages of the principal strewn fields, as well as for some impact glasses whose association with tektites is claimed by some authorities. The good agreement of almost all members of the Australasian strewn field with one another is striking, and has had a strong influence on all thinking about the tektite problem. These ages agree well with the ages of the microtektites of the Australasian strewn field, as these have been

determined by magnetic stratigraphy and biostratigraphy. In conjunction with the chemical evidence (Chapter 6) they strongly suggest that the Australasian strewn field is a single unit.

Similarly the K-Ar age of the Ivory Coast strewn field is confirmed by the magnetic stratigraphy of the sediments in which the microtektites are found (Glass, 1968); and the K-Ar age of the North American strewn field is confirmed by the stratigraphic age of the North American tektites both on land, where they are found in late Eocene sediments (Jackson), and at sea, where they are reported from sediments of middle Upper Eocene (based on Radiolaria) (Glass et al, 1973).

McDougall and Lovering (1969) found K-Ar ages for 13 australite cores of 0.86 ± 0.06 m.y. (mean error). The discrepancy with Zähringer's results is perhaps due to the fact that Zähringer did not use a ^{38}Ar tracer; it is not due to any kind of scale error because they found 14.4 m.y. for a moldavite, inserted as a check. The size of the discrepancy indicates the need for caution; the consistency of the measurements for the Australasian strewn field in Table 7-1 cannot be used as an indicator of the true errors.

The same authors (1969) also measured ages on the flanges of australites; for 6 cases they found an age of 1.18 ± 0.28 m.y., i.e. older than the cores. The most hopeful explanation of this result,

which has been noted (but not published) elsewhere, is that the australites had some inherited argon when they entered the atmosphere; and that this concentrated in the flange. The argon is definitely ⁴⁰Ar, and therefore did not come from the atmosphere.

Fission-track ages

An entirely independent method of dating the latest heating episode in tektite glass was devised by Fleischer and Price (1964b); it results from the natural fission of ²³⁸U. The fission fragments leave damage tracks in the glass which can be detected by etching, followed by optical microscopy. To determine the amount of uranium in the glass, a comparison specimen is bombarded with thermal neutrons, which cause a similar fission of ²³⁵U, and thus allow measurement of the uranium content by comparable techniques.

Ages determined in this way are shown in Table 7-1, together with the K-Ar ages. It is clear that the two are closely comparable, but a number of interesting new features appear.

In the first place, Gentner et al (1969b) showed that the fission-track ages of australite flanges are equal, within the errors of measurement, to the ages of the corresponding cores. This point is critical in considering the question of the ages-on-earth of the australites. If the flanges were produced by passage through the atmosphere, which is not seriously questioned by anyone, then these

fission-track ages must be the true ages on earth of the australites; they cannot have the ages-on-earth assigned to them by the careful geological studies mentioned in Chapter 2.

In the second place, the Libyan Desert glass can be dated by fission-track methods (the low K content makes difficulties for the K-Ar method). This glass was at first believed (Fleischer et al, 1965b) to be simultaneous with North American tektites; but later work (Gentner et al, 1969b) demonstrated that they are some 8 million years younger.

The Darwin glass (Gentner et al, 1969b) was shown to have the same fission-track date as the Australasian strewn field, of which it seems to form part.

The high-sodium tektites discovered by Chapman and Scheiber (1969b) were found to have fission-track ages of 4 m.y., some 5 or 6 times as large as the age of the other Australasian tektites. Since these tektites are similar in shape and in geographic location to other Australasian tektites (though no flanged forms have been found yet) they pose a very serious puzzle. Do they represent a new strewn field? Or can tektites be sent somehow from their source region to the earth without erasure of the fission tracks? If the second alternative is correct, then the source can scarcely be terrestrial meteorite impact; no reservoirs of tektite glass are known

and it is not credible that an event of such violence as to fuse tektite glass should leave fission tracks untouched.

It has also been possible to obtain fission-track ages of microtektites from the Australasian strewn field, the Ivory Coast strewn field, and the North American strewn field (Gentner et al, 1970a, and Glass et al, 1973). The results confirm the hypothesis that microtektites are genuinely part of the same phenomenon as the land tektites; they also furnish the strongest evidence that the Australasian and Ivory Coast strewn fields are really two different events, and not, as Chapman and Scheiber (1969b) suggested, parts of the same strewn field.

A persistent problem with the fission-track method is the tendency of the tracks to fade with time. Fleischer and Price (1964c) considered that glass from Clearwater Lake had an age of 33.5 m.y., and was related to the North American strewn field. Later, however (Fleischer et al, 1968), the low age was attributed to track fading; the age was revised to 100 to 300 m.y. Methods for correcting for track fading have been brought forward by Storzer and Wagner (1969) and utilized by Gentner et al (1969b).

Georgia tektites in particular persistently give fission-track ages which are lower than their K-Ar ages, and are inconsistent with each other. They are found apparently weathering out of the mottled

clays of the Hawthorne formation; the mottling is due to a patchy local oxidation. Is it possible that the oxidation heats the clay locally, and so causes track fading? An almost identical tektite from Martha's Vineyard, Massachusetts, gives a fission-track age of 35.5 m.y. (Fleischer et al, 1965b). Even after correcting for track fading, Storzer and Wagner obtained ages ranging from 1.0 to 34 m.y. for Georgia tektites.

Rubidium-strontium ages

The decay of ^{87}Rb to ^{87}Sr , with a half life of 60 billion years, also furnishes a way of measuring ages of rocks. In this case, the age is not necessarily the age since the rock was last strongly heated; instead it is the age since the relation of rubidium to strontium was last disturbed. Rubidium, like other alkali elements, tends to concentrate in sialic rocks; hence Rb/Sr ages are ages since the rock was last differentiated.

It is customary to plot the ratios of the isotopes $^{87}\text{Sr}/^{86}\text{Sr}$ against the ratio of rubidium to strontium. See Fig. 7-1. For a well-mixed glass which had just been made, there would be a single point giving these two ratios. If now the glass should be differentiated, say by the crystallization and loss of pyroxenes or olivine, so that the alkalis, which are left behind, are concentrated to varying extents in various parts of the melt, then a horizontal line would be produced.

It would be horizontal because these chemical processes are expected to change the Rb/Sr ratio, but not (to any measurable extent) the ratio of the two Sr isotopes.

Thereafter, the decay of ^{87}Rb to ^{87}Sr would move the point corresponding to each specimen upward and to the left. (Owing to the long half-life of ^{87}Rb , in comparison with the times here involved, it turns out that the scale needed for $^{87}\text{Sr}/^{86}\text{Sr}$ runs only from 0.699 to, in most cases, 0.720, while the ratio of Rb to Sr ranges by large factors.) Clearly the amount of ^{87}Sr generated is proportional to the amount of ^{87}Rb (and hence to the total Rb) in the original material; on the other hand, the amount of ^{86}Sr is proportional to the total Sr; thus the rate of movement of a point on this graph (as geological time proceeds) is proportional to the Rb/Sr ratio. This converts horizontal initial lines into inclined straight lines. The slope of the straight lines measures the age since differentiation, and its intercept on the axis of $^{87}\text{Sr}/^{86}\text{Sr}$ measures the initial value of this ratio (since with zero Rb, this ratio would not change).

When this method is applied to an actual rock or a collection of rocks, one hopes to obtain a more or less linear array capable of being interpreted as described. Two choices are now open for interpreting the diagram:

Isochron age

If the array is convincingly linear, a straight line can be put through the points, and an age, called an isochron age, can be found from the slope of the line. The intercept on the vertical axis yields the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

Model age

If the array does not appear linear, it may still be possible to extract an age from it, if one can assume a value for the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Marking this value off on the vertical axis, a line can be drawn through the centroid of the distribution of points; the slope of this line determines what is called a model age.

When these methods were first applied to tektites, Pinson et al (1958) found very low ages - too low to measure - assuming an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.712. Later Schnetzler and Pinson (1964b) found that the centroids of the distributions for the three strewn fields which they could then study (the Australasian, moldavite, and bediasite fields) lay on a straight line on the standard plot. The intercept corresponded to $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7050, and the slope yielded an age of 400 m.y.

However, when Schnetzler et al (1966) measured the Rb/Sr data for the Ivory Coast tektites, they found that the center of the distribution did not fall on the 400 m.y. isochron defined by the other three strewn fields. Their graph is shown as Fig. 7-1.

Schnetzler et al also measured the Rb/Sr age of the rocks at the Bosumtwi crater, Ghana; these rocks yielded a very clearcut isochron with an age of 1.97 b.y., and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of about 0.702.

The age of the Ivory Coast tektites from these data would be about 1 b.y. for the isochron method (though even zero appears to me a possible value; the array is not strongly inclined); it would be somewhat greater than 2 b.y. by the use of an initial value near 0.700. Schnetzler et al noted that the Bosumtwi rock isochron passes through the right-hand end of their distribution. They suggested that all the Ivory Coast tektites had originally lain on the Bosumtwi isochron, but that differential volatilization, occurring during the Bosumtwi impact event, had moved most of the tektites to the left.

This explanation appears to be somewhat ad hoc, although Lippolt and Wasserburg (1966), who also measured the Rb-Sr relations, adopted the same explanation. Schnetzler et al (1966) supported their ideas by referring to the work of Walter and Carron (1964) on vapor fractionation of tektite melts; these results indicated that Rb volatilizes rapidly from a melt, like Si, but more rapidly than Sr. Hence the tektites of lowest Si ought to be those of lowest Rb/Sr, if volatilization is the correct explanation; and in fact it is found that tektites of high index of

refraction (and presumably low Si) are those of lowest Rb/Sr.

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From the physical standpoint, the loss of rubidium (and silica) seems unrealistic. The specimen would surely have to boil, as in the case of argon loss. But in free space it would be expected that boiling would break the object to small pieces, like volcanic ash, or like microtektites. Yet there are Ivory Coast tektites weighing on the order of 100 grams.

It is important to see, on the other hand, that in effect both Schnetzler et al (1966) and Lippolt and Wasserburg (1966) were interpreting the data in terms of an isochron age which is the same as the K-Ar age. This age is the age since the volatilization event, in their theories; but so far as the data go, it could equally well be the age since differentiation.

The moldavite-Ries relation was studied by Philpotts and Pinson (1966) and by Schnetzler et al (1969). No relation between the Ries and the moldavites was found, in the matter of Rb-Sr abundances. The moldavites showed no measurable correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ over a fairly wide range in Rb/Sr; i.e. the isochron was nearly level. This suggests an age less than 50 m.y. if straightforwardly interpreted. The authors note the similarity to relations among the Ivory Coast tektites. They suggest a number of hypotheses, including volatilization. The simplest hypothesis is

that originally put forward by Pinson et al (1958), namely that the isochron age is the true age of differentiation. Then the tektites must have formed from a parent magma at some time in the last 50 m.y., possibly at the date given by the K-Ar age of 15 m.y.

The Rb-Sr relations in the Australasian strewn field were studied by Compston and Chapman (1969). They found that the Rb-Sr relations among Australasian tektites are different for different clans. The high-magnesium clan gives an age of 100 ± 30 m.y.; the high-calcium clan an age of 265 ± 20 m.y. They considered that these results might indicate a number of different igneous suites on the moon; alternatively, the results might indicate meaningless mixtures of lunar volcanics or terrestrial sediments.

The Rb-Sr studies of the North-American tektites showed so little spread in Rb/Sr that no isochron could be drawn (Schnetzler and Pinson, 1964b).

The Rb-Sr data taken as a whole indicates clearly that tektites differentiated at dates much more recent than the formation of the moon. If we look at the isochron ages rather than the model ages, it is seen that for many tektite groups ages not far from the K-Ar age seem to be possible.

Lead-uranium-thorium methods

From examination of lead samples, both terrestrial and meteoritic, it has been found (York and Farquhar, 1972) that it is

possible to explain many of them (the conformable leads) by the following discussion:

Theory

When the earth formed, at about -4.55 b.y., the atomic abundances of the isotopes of lead, uranium, and thorium were as shown in Table 7-2, col.3. The decay of the three radioactive parent nuclides, ^{232}U , ^{235}U , and ^{238}U , each involves a slowly decaying parent isotope, a number of relatively rapid intermediate radioactive transformations, and a non-radioactive lead isotope at the end. When we are thinking in terms of millions of years, the intermediate steps can be forgotten (the longest, for ^{234}U , is 250,000 years¹), and we can treat the problem as if the parent nuclides decayed directly into lead.

Among the lead isotopes, four are stable. One is non-radiogenic, namely ^{204}Pb . Each of the other three may be formed from a radioactive decay chain: ^{206}Pb from ^{238}U , ^{207}Pb from ^{235}U , and ^{208}Pb from ^{232}Th . It may be useful, in remembering these associations, to note that the two odd isotopes, ^{207}Pb and ^{235}U , are associated; also that the two isotopes with atomic weights divisible by 4 are associated, namely ^{232}Th and ^{208}Pb . Note also that since one atom of the parent element forms one atom of the final isotope, the sum of the atomic abundances ($^{238}\text{U} + ^{206}\text{Pb}$, for example) is constant in time.

These very schematic ideas happen to suffice for dealing with most problems involving tektites; for terrestrial rocks and minerals there are numerous complications, particularly those due to leaching by ground water.

At any time t , after the formation of the earth (at -4.55 b.y.), the amount of any radioactive isotope, say M , which survives,
 as in 7.1
 is given by

$$M = M_0 e^{-\lambda t} \quad 7.4$$

where λ is the decay constant given in Col. 2 of Table 7-2, and M_0 is the initial abundance of the parent radioactive isotope. The atomic abundance of the corresponding lead isotope, D , is therefore given by

$$D + M = D_0 + M_0$$

where D_0 is the initial abundance of the lead isotope. Then, as in 7.3

$$D = D_0 + M_0 (1 - e^{-\lambda t}) \quad 7.5$$

In Col. 4 of Table 7-2 are the abundances of the relevant isotopes as they are believed to exist in the mantle of the earth today; the lead is common or modern lead.

The very schematic presentation in Table 7-2 does in fact account simultaneously for the lead isotopes in at least some iron meteorites (where there has never been any significant U or Th) and for the abundances of lead isotopes in lead ores, especially galena (PbS) both ancient and recently formed.

Application to tektites in general

Tektite leads are always modern leads, as was first pointed out by Tilton (1958); i.e. the lead isotope abundance ratios are those of Col. 4 of Table 7-2. On the other hand, the abundances of U and Th, relative to lead, are not those of Col. 4, Table 7-2. Relative to lead, the uranium and thorium are enhanced by factors of 3 to 6. Table 7-3 was recalculated from Tilton (1958) to put it in the form of Table 7-2. It is seen at once that while the leads are indistinguishable from modern leads, the uranium is enhanced by a factor of 4, and the thorium by 6.

These enhancements are a normal feature of magmatic differentiation, which enhances elements which do not fit easily into the crystal lattices of olivines and pyroxenes. Similar enrichments are seen in most differentiated rocks, especially the more silicic ones.

When did the enhancement occur? One can easily verify by numerical experiments that the differentiation could not have occurred as early as -200 m.y.; this would have yielded a value of 19.8 for $^{206}\text{Pb}/^{204}\text{Pb}$. As Tilton remarks, the differentiation process must have taken place in the last 50 m.y.

It is also a result of these studies that in all probability tektites are the result of the differentiation of a material very much like the mantle of the earth in its U-Pb-Th ratios.

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Starik et al (1959) analyzed an indochinite, and obtained the startling figures (in units of ^{204}Pb): ^{206}Pb , 28.9; ^{207}Pb , 17.5; and ^{208}Pb , 41.9; these figures imply an age of approximately 4.5 b.y. since differentiation. This work may have been in error; in later work (Starik et al, 1961) they found essentially the same result as Tilton: the lead is modern lead, but the uranium is enhanced by a factor of 2 to 5 with respect to the lead. They note that in sedimentary rocks, the Pb/U ratio is usually much greater. The Pb/U ratio in the Libyan Desert glass specimen which they studied approaches the equilibrium value, so that its age of differentiation is not well determined; but the other tektites all have to be young. They concluded (Starik et al, 1962a, 1963) that neither igneous rocks nor sedimentary rocks nor meteorites were plausible parents for tektites.

Rowe et al (1963) measured the thorium contents of tektites, including Libyan Desert glass, which had not been done previously. Rybach and Adams (1969a) measured U, Th, K but not Pb for Ivory Coast tektites; they found them similar to the Bosumtwi crater glass.

Bosumtwi - Ivory Coast

Wampler et al (1969) studied the uranium-lead relations in the Ivory Coast tektites and Bosumtwi crater glass. For uranium, their results are generally in agreement with Rybach and Adams (1969a)

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but less consistent. They found that the lead in the Ivory Coast tektites is close to modern lead; but the uranium has been enriched relative to lead by a factor of 3 to 6, as usual; hence it is difficult to understand how tektites could have been differentiated at -2 b.y. One would calculate a value of 24.6 for $^{206}\text{Pb}/^{204}\text{Pb}$, for instance. In the Bosumtwi crater glass, they found little enhancement of the U/Pb ratio; here also modern lead was encountered. For the Bosumtwi phyllites (metamorphosed shales), the $^{238}\text{U}/^{204}\text{Pb}$ ratio is 16, rather than 25 or more, as with the tektites. Since the equilibrium value is 9.2, the phyllite data indicate an enrichment of U relative to Pb of 1.7. The calculated value of $^{206}\text{Pb}/^{204}\text{Pb}$ after 2 b.y. is 21.5; the actual value is 18.0.

The result with the phyllites is clearly an unfortunate coincidence; it is clear that in general it is unusual, in such ancient rocks, to come across lead so modern (cf. the lists of lead isotope data in Russell and Farquhar, 1960). It is probable that the cause of the modern lead in the Ivory Coast tektites is the same as that in all other tektites.

Summary and conclusion from isotopic age dating

Summing up the results of these age studies, let us note that the simplest possible hypothesis does not seem to be excluded, namely that in each strewn field the K-Ar, fission-track, Rb-Sr and lead ages are all telling us about the same event, and all are giving the

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same ages, within their accuracies. This is the first hypothesis that would be tested for a terrestrial obsidian; since tektites look like obsidians, and were called obsidians by most of the 19th century investigators, it may be that this idea should have priority here also.

It is evidently possible that the lead ages and the K-Ar ages are actually the same. For the Rb-Sr ages, the data for the moldavites directly suggest a very young age; the data for the North American tektites are not in disagreement; and for the Australasian tektites, the high-magnesium group suggests a very low age, though not as low as the K-Ar. For other Australasian tektites, a higher age is suggested; but this may be due to mixing. For the Ivory Coast tektites the same is true.

The stratigraphic age of tektites is usually close to their isotopic age. This suggests that they were thrown from their source region by the same processes, presumably volcanic, as those which reset the isotope clocks and the fission-track clock. The high-sodium tektites would then be an isolated example of material heated and ejected in one eruption, but not then thrown far from the source. They would then have been picked up and launched in the great eruption which produced the Australasian strewn field. If this is right, then a flange of a high-sodium australite might give an age of -700,000 years, while the core gives an age of -4 million.

ISOTOPIC AND FISSION-TRACK EVIDENCE CONCERNING
AGE-IN-SPACE

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Age-in-space vs. age since last melting

Primary cosmic rays encountering silicates produce a large number of radioactive isotopes, in contrast with the much feebler secondary cosmic ray particles which reach the earth's surface. Radioactive isotopes produced by primary cosmic rays have been detected in meteorites. They can be distinguished from the so-called naturally radioactive isotopes, which have survived since the formation of the solar system, because the natural radioactivities all have half-lives on the order of 1 billion years or longer, for the obvious reason that those of shorter half-life have already decayed.

Aluminum-26

Ehmann and Kohman (1958a) set up a search for all radioactivities with half-lives less than 10^9 years. They believed (1958b) that they had found evidence for ^{26}Al (half-life 0.740 m.y.) and ^{10}Be (half-life 2.7 m.y.) in the Australasian tektites. Viste and Anders (1962), however, searched for ^{26}Al by looking for the pairs of gamma rays that are produced when the positive electron from ^{26}Al is annihilated by coalescing with a normal electron. Their finding was that the ^{26}Al , if present, was present only at

levels much below those found by Ehmann and Kohman. Viste and Anders found an upper limit to the exposure time in space of 90,000 years, provided that the tektites arrived as small, unshielded bodies.

Evidently these calculations are vitiated if the tektites arrived as a single, large body for each strewn field, since in that case the outer parts would shield the inner parts. Viste and Anders calculated that if the radius of the hypothetical large parent body was less than 54 meters, then they would have had a fair chance of finding irradiated fragments; this would be about 2 million tons, which Viste and Anders considered to be more than the total mass of the Australasian strewn field. On the other hand, the microtektite data (Glass, 1972a) indicate that the total mass of the Australasian strewn field is near 100 million tons. Thus the validity of the results of Viste and Anders depends on the elimination of the parent-body hypothesis for the origin of tektites.

The microtektite data, however, are probably inconsistent with the arrival of the tektites of a single strewn field in a single mass (O'Keefe, 1969c). It is not possible to explain the wide range of composition in microtektites as the result of ablation from a single parent body. In addition, in order to produce the extensive strewn fields from a single body, it is necessary (O'Keefe and Shute,

1963) to suppose that tektites arrived at very low angles (less than 3°) to the horizon. But Chapman and his coworkers have produced evidence (see Chapter 3) that in the case of the australites, at least, the descent occurred at relatively steep angles (of the order of 30°), which would exclude arrival as a single body, and would mean that the ^{26}Al measurements do limit the age of tektites in space to less than 90,000 years.

The basic justification for the parent-body hypothesis was originally Urey's point that if tektites arrive from the moon as a shower of independent bodies, then we must explain why the great majority of tektites, which will surely miss the earth on the first pass, do not go out into orbit, and strike the earth later. The parent-body hypothesis became superfluous when Paddack (1969) demonstrated that radiation pressure can destroy non-conducting bodies in space by spin-up to rotational bursting (the Radzievskiy-Paddack effect).

Since the Radzievskiy-Paddack effect does not affect large bodies, Cressy et al (1972) looked for ^{26}Al in the Aouelloul crater glass. The point is that if the hypothetical large glass meteorite had been launched from the moon, it would probably have gone into heliocentric orbit; the crater would then result when the object encountered the earth a million or so years later. The results

were negative; in the light of the ages found by Fleischer and Price (1967) of around 0.5 m.y., this seemed highly significant. Unfortunately Storzer (1971) revised the track ages of the Aouelloul glass, allowing for track fading, and found 3 m.y. Since the half-life of ^{26}Al is 0.74 m.y., the ^{26}Al would have fallen to 6% of the initial amount, and would not be detectable.

Neon-21

Reynolds (1960) looked for ^{21}Ne in tektites. The test is very sensitive; he found that the time of flight must, in the case of some Australasian tektites, have been less than 28,000 years. These results were discounted at first because, as Viste and Anders (1962) remarked, it seemed plausible that tektites might have been outgassed during entry into the earth's atmosphere; this was especially true on the basis of the parent-body idea. But numerical and physical studies (Chapman, 1964) show that the ablative heating does not penetrate the whole tektite; and the parent-body idea is not needed; thus the test retains its validity. Shielding should be discounted, as noted above.

Neon diffuses out of tektites in a time of the order of a few million years according to the theoretical calculations of Reynolds (1960). These are supported by my previously unpublished observation that neon in tektite vesicles is much less abundant in

Australasian tektites than in moldavites (kindly loaned to me by R. Rost) or bediasites. It follows that the ^{21}Ne test does really indicate an age-in-space of less than 28,000 years for the Australasian tektites.

It would probably be useful to try this method on the Aouelloul crater glass; according to Cressy et al (1972) shielding effects should be negligible.

Carbon-14

Boeckl (1972) looked for ^{14}C in some australites. If australites had in fact fallen within the last 20,000 years, and had previously traveled through space for a similar period, then it might have been possible to find ^{14}C ; the results were in fact negative.

Cosmic-ray tracks

Fleischer et al (1965a) noted that primary cosmic rays passing through tektite glass will produce V-shaped tracks. The primary particle causes fission in nuclei of Th, U, and occasionally Pb, while the nucleus is in motion; they are thus distinguishable from the tracks produced by fission when the particle is at rest: in the latter case, the fission fragments must go out in directions precisely opposite.

Cosmogenic tracks have been sought in tektites; they were not found. Fleischer et al (1965a) showed that, at least in the case of australite buttons, there are regions of the tektite which were never

heated enough to erase the tracks. From the total absence of cosmogenic tracks, Fleischer et al were able to set low limits to the time spent by tektites in space; the maximum flight times ranged from 900 to 6000 years, and include Australasian tektites, an Ivory Coast tektite, a moldavite and a bediasite.

From all these measurements, it is clear that tektites spent at most a few thousand years as separate, unshielded bodies in space.

STABLE ISOTOPES

A few stable isotope abundance ratios, particularly among the lighter elements, can be disturbed by chemical processes. These ratios therefore serve the same function as chemical analyses, in giving some indication of possible relations with other materials.

Deuterium/hydrogen

The ratio of deuterium to hydrogen (D/H) was measured by Friedman (1955, 1958). It was found to be similar to that in terrestrial obsidians, ranging from 0.0132 to 0.0166 percent.

Values of D/H are customarily given as δD per mille (‰) relative to standard mean ocean water; the relation is

$$D/H \times 10^6 = 0.158 (1000 + \delta D) \quad 7.6$$

Friedman et al (1974) report that the analysis of water from lunar sample 66095 (the rusty rock) yielded δD -75 to -140 per mille,

not unlike terrestrial rocks or tektites, and very different from most previously reported lunar hydrogen, most of which seems to be trapped solar wind, with values around -850. They consider, contrary to Epstein and Taylor (1974), that the water cannot be from the earth's atmosphere, because it has a value of the ratio $^{18}\text{O}/^{16}\text{O}$ which is distinct from that of water from the earth's atmosphere, and like that in lunar rocks.

Oxygen isotopes

The relation of ^{18}O to ^{16}O is usually expressed in the form

$$\delta^{18}\text{O} = \left\{ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right\} 1000 \quad 7.7$$

where R is the ratio, $^{18}\text{O}/^{16}\text{O}$, and the standard is mean ocean water.

Baertschi (1950) found +9.5 (javanite) to +11.5 (moldavite) per mille relative to Hawaiian sea water; Darwin glass he found to be +15.5 in the same units. Silverman (1951) found +10.4 for a moldavite and a philippinite. H.P. Taylor and Epstein (1962, 1964) found +8.9 to +10.8 for various tektites (Australasian, moldavites, a bediasite). Libyan Desert glass gave +10.2. They then noted that sediments and metasediments generally give higher values, in the range +12 to +18. But in a later paper (H.P. Taylor and Epstein, 1966) they found that Ivory Coast tektites give values of +12.8 to +14.6, i.e. outside the range of previously measured tektites other than Darwin glass.

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They found that the Bosumtwi crater glass from Buonim creek gave +14.8, while that from Ata gave +12. Though neither measure falls in the range of the tektite oxygen values, the mean agrees closely with the tektite mean. If the Buonim material of Taylor and Epstein is the same as the Boni material of Cuttitta et al (1972) then it is chemically not as much like Ivory Coast tektites as the Ata material. Thus Cuttitta et al, in making their comparison, persistently refer to the green and black (Ata) glasses, excluding from their comparisons the grey (Boni) glass which they also measured. If we compare Ata glass (+12) with Ivory Coast tektites ($+13.7 \pm 0.8$), the Student t-test indicates that the probability is 0.1 that they are the same. Evidently the relation cannot be claimed as evidence that the Ivory Coast tektites come from Bosumtwi.

Lunar values cluster around +5 to +6 per mille relative to standard mean ocean water; there are no significant lunar measurements which yield values above +7 (H.P. Taylor and Epstein, 1973). On the other hand, all lunar measurements are made on rocks of more or less basaltic composition, except the measures on the silicic part of specimen 12013. On the earth, basaltic rocks give similar values of $\delta^{18}\text{O}$. Most silicic igneous rocks give values like tektites. Specimen 12013 (H.P. Taylor and Epstein, 1970) gives $\delta^{18}\text{O}$ in the range +5.9 to +6.5, like the lunar basalts, and

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not like tektites, nor like terrestrial acid igneous rocks. The specimen is a mixture of silicic and basaltic rock, in close contact (regions a centimeter or so across), so that the possibility arises that the O-isotope values resulted from equilibration with the basalt. Taylor and Epstein (1970) consider and reject this possibility, on two grounds:

a. They consider that most terrestrial granites are metamorphosed sediments; they would therefore expect lunar silicic rock to resemble the rare rhyolitic glasses from oceanic islands, which have $\delta^{18}\text{O}$ around +5 to +6.

b. They note that the initial values of the $^{87}\text{Sr}/^{86}\text{Sr}$ vary from point to point within specimen 12013. This means that the Sr did not equilibrate isotopically; they infer that oxygen would not have equilibrated.

Both arguments are plausible, but neither is compelling. Many students of terrestrial granites think that most granites are not derived from sediments, and hence that the higher $\delta^{18}\text{O}$ is somehow the result of magmatic differentiation, in which case it might occur on the moon. Second, the diffusion coefficient for oxygen may well be larger than for strontium (personal communication from A.R. Cooper); hence the fact that the Sr isotopes were not equilibrated does not give us assurance that the O isotopes were not

equilibrated. They might have been; if they were, then the $\delta^{18}\text{O}$ may come from the basalt and may not be representative of lunar silicic rocks.

Silicon isotopes

The silicon isotope ratios were measured by Tilles (1961), in terms of a parameter δ defined by

$$\delta = \left\{ \frac{{}^{30}\text{Si} / {}^{28}\text{Si} + {}^{29}\text{Si}_{\text{sample}}}{{}^{30}\text{Si} / {}^{28}\text{Si} + {}^{29}\text{Si}_{\text{standard}}} - 1 \right\} \times 1000 \quad 7.8$$

Out of 7 measurements, all except one (a bediasite) lay in the range 0 to -31 per mille relative to a vein quartz standard. The range is small compared to terrestrial sediments, but compares closely to the range in lunar rocks (H.P. Taylor and Epstein, 1973).

CONCLUSIONS

From the isotopic data, the following conclusions appear probable:

a. There are six known tektite strewn fields. In order of age they are:

- (1) Australasian, age 0.75 m.y.
- (2) Ivory Coast, conceivably identical with (1), age 0.9 m.y.
- (3) Aouelloul, age 3 m.y. (Disputed).
- (4) Moldavite, age 15 m.y.
- (5) Libyan Desert glass, age 28 m.y.
- (6) North American strewn field, age 35 m.y.

b. Lead ages of tektites are reconcilable with their K-Ar and fission-track ages. The Rb-Sr ages are not unmistakably inconsistent with the same ages; it is difficult to see why they should not agree with the lead ages, and in some cases, especially the moldavites, they seem to. Conceivably all four ages refer to the same event.

c. Tektites did not sojourn in space longer than about 900 years.

d. The D/H ratios in tektites may be consistent with lunar water, at least from the rusty rock (66095).

e. O isotope ratios in tektites are generally like those in terrestrial acid igneous rocks. They disagree with the only known lunar acid rock; but the meaning of the disagreement is not clear. Except for Ivory Coast tektites they disagree with most terrestrial sedimentary rocks.

f. Silicon isotope ratios in tektites are like those in lunar rocks and not like those in terrestrial sedimentary rocks.

CHAPTER 8

THE TERRESTRIAL ORIGIN OF TEKTITES:

ARGUMENTS IN FAVOR

In this chapter the arguments for the terrestrial origin of tektites will be critically reviewed. The main topics will be:

- a. Arguments based on the geographic distribution of tektites.
- b. Arguments based on the chemical and isotopic comparisons of tektites with terrestrial and lunar rocks.
- c. Miscellaneous arguments.

ARGUMENTS BASED ON THE GEOGRAPHIC DISTRIBUTION OF TEKTITES

An important boundary condition on theories of the origin of tektites is the generally accepted proposition that they cannot come from beyond the earth-moon system. The first demonstration of this fundamental proposition was by Urey (1955). He argued that a cloud of small bodies in orbit around the sun would be unstable if the density was less than the Roche limit (Tisserand, 1896, Vol IV, pp.245-249) which can be put in the form

$$\rho_c < 2\rho_o$$

8.1

where ρ_c is the density of the cloud, and ρ_o is the density of a mass equal to the mass of the sun, distributed over a sphere whose radius is the distance from the sun to the cloud. Numerically

$\rho_c = 2.8 \times 10^{-4} \text{ kg m}^{-3}$. If the tektites of the Australasian strewn field had ever moved about in space they would presumably have formed a cloud whose diameter would be of the same order as the Australasian strewn field, namely 8800 km. With the above density, the mass in a column going through the cloud would be $2.4 \times 10^5 \text{ kg m}^{-2}$. When the cloud struck the earth, it could be expected to produce a surface deposit of this density. The actual surface density in the Australasian strewn field is estimated by Glass (1972a) as $10^{-3} \text{ kg m}^{-2}$; and this estimate is free from the objections about losses by aboriginal man, stream action, birds, mechanical erosion, fusion stripping, sand-blasting, rolling, and probably even solution etching, raised by Baker (1960a), since Glass's estimate depends almost wholly on the density of microtektites at the bottom of the sea.

Hence a cloud of tektites arriving from space would necessarily have had too low a density for stability. Then, unless the space trajectory was very short, the tektites would have formed a cloud with dimensions greater than the earth. It follows that, instead of the observed strewn fields, there would have been a distribution over a whole hemisphere of the earth, as is observed in meteor showers. Since this is not what happens, it is generally agreed that origins more remote than the moon can be excluded.

Chapman (1964, 1971) showed that the existing strewn fields

are reconcilable with origin from the moon, provided that the tektites come directly from the moon. Urey (1963) referred to earlier versions of this idea, and made the point that if tektites are from the moon, then in any burst of tektites, the great majority ought to miss the earth and go into heliocentric orbit. They would then eventually strike the earth, and would form a conspicuous population of tektites distributed at random over the earth, which is not observed; and he concluded that they must be terrestrial.

O'Keefe (1963b) and O'Keefe and Shute (1963) made an abortive attempt to meet Urey's objection by supposing that tektites enter the atmosphere from decaying, nearly circular orbits, derived from a single, large parent body for each strewn field. The large parent body was an essential part of the theory; with more than one parent body, there would be a range of decaying orbits, and hence a distribution completely around the earth. The parent-body idea had to be given up (O'Keefe, 1969c) when it became clear that the microtektites could not be explained as ablation drops from the same parent body as the large tektites; and hence that they were apparently independently launched from the same source as the macrotektites and at the same time.

It thus follows that the terrestrial origin of tektites must be

the true one unless there is some mechanism in space which prevents tektites, once launched into heliocentric space, from being recovered by the earth. Urey (1963) pointed out that the Poynting-Robertson effect will require about 10 million years to destroy a particle of 1 cm radius, while capture by the earth will, he calculated, require only a few times 10^5 years; similarly space erosion at the expected rate of about 1 nm per year is too slow.

Radzievskiy (1954) showed (in a different connection) that such a mechanism does exist. He found that radiation pressure will exert a torque on a body if the albedo on one side differs systematically from that on the other (as in a Crookes radiometer). The two sides involved here are not the front and back, for instance, (Fig. 8-2) but the left and right sides as viewed from the sun. He took as an example a cube, rotating around a vertical axis perpendicular to the direction of radiation. If, on each of the vertical faces, the left side is black, and the right is white, then the cube will rotate in the counter-clockwise direction. In sunlight, the cube will spin up to bursting speed in a few times 10^4 years if the albedo difference is systematically as much as about 1%.

Paddack (1969, 1973) further showed that an object of helical shape will be set into rotation by light directed along its axis. (Fig. 8-2) He found that there is a significant helical component in the external

shapes of ordinary pebbles. Like the Radzievskiy effect, the Paddack effect leads to ages which are orders of magnitude less than the Poynting-Robertson effect; hence Urey's argument against a cosmic origin for tektites cannot be extended to exclude a lunar origin.

The isotopic studies on ^{26}Al (Viste and Anders, 1962) and ^{10}Be (Rayudu, 1963) (Chapter 7) indicated an upper limit of about 10^5 years for the residence-time of the Australasian tektites in space; and a narrower limit of less than 10^3 years was set by fission-track studies (Fleischer et al, 1965a).

An extension of Urey's argument was made by Barnes (1958a) and Kopal (1958), who argued that the structure within a given strewn field is so fine that it is difficult to believe that tektites originate at the moon. For example, the Bohemian and Moravian portions of the moldavite strewn fields are each only about 50 kilometers in width. Similarly McColl and Williams (1970) find that there is a high concentration of australites in long narrow bands less than 100 kilometers in width.

This fine structure can perhaps be understood, even in terms of a lunar origin, if there is a gas accompanying the tektites at the source region. The gas will entrain the tektites, so that all tektites in a given region will move with the same velocity, namely

the gas velocity. Mixtures of this kind are well-known in studies of atomic explosions: they are called ensembles. (Note that if the gas is at rest in a gravitational field, the velocities of the solid particles contained in it will tend toward a terminal velocity, which, for the case of the earth, is a few tens to hundreds of meters per second; but if the gas is moving on a ballistic trajectory, then the velocities of the solid particles will tend toward zero with respect to the gas, and therefore with respect to each other.) If the relative velocities are reduced to a few tens of centimeters per second, then, even in the passage from the moon to the earth, the fine structure will not be smeared out at the level of tens of kilometers. The gas will have cooled as a result of expansion; this will reduce its tendency to expand further. A quantitative treatment would be valuable, taking into account the focussing effect of the earth's field.

CHEMICAL AND ISOTOPIC ARGUMENTS: S.R.TAYLOR'S REVIEW

The strongest arguments for the terrestrial origin of tektites, and against the lunar origin, are in the field of chemical and isotopic studies. These arguments have been ably reviewed by S.R.Taylor (1973), using Apollo results. In this section, Taylor's arguments for his theories will be stated, point by point, omitting

those points which do not bear on the question of terrestrial versus lunar origin. Each point will be followed by a comment (of mine). The headings are from his paper.

Chemistry

Point: Tektites and impactites seem to favor the high-silica end of the petrological sequence; SiO_2 less than 65% by weight is rare.

Comment: A large fraction of the microtektites, perhaps the majority, have SiO_2 less than 65% (Cassidy et al, 1969); the Lonar Lake impact glasses are around 50% SiO_2 (Fredriksson et al, 1973). Hence there are no physical barriers to low-silica tektites or impactites.

Point: There is a narrow range in tektite composition; it suggests that tektites are the result of a process of natural selection; somehow rocks outside this range fail to form tektite glass.

Comment: The most important parameter governing the physical performance of tektite glass is undoubtedly silica content, especially through its influence on viscosity. But tektites cover a wider range of silica content than most types of terrestrial igneous rocks, namely from 49 percent to 98 percent; this results in a range in viscosity which has never been measured, but is

certainly more than six orders of magnitude.

If Taylor's hypothesis were right, we would expect tektites to show a relatively small range of silica content, and a wide range in other oxides. But in fact the range in silica is comparatively wide, and that in other oxides, at a given silica content, remarkably narrow, especially for a given tektite clan.

Point: Aouelloul glass is identical with Zli sandstone, according to Cressy et al (1972).

Comment: Cressy et al measured five elements and the Sr isotope ratios; the agreement was good, but there are other elements for which agreement is not good, including Ca, Fe (O'Keefe, 1971) and a series of trace elements (Annell, unpublished). The glass has much lower water content and ferric-ferrous ratio.

Point: Australites are chemically like Henbury impact glass (i.e. well-studied tektites often resemble well-studied sandstones).

Comment: The resemblance does not include water, ferric-ferrous ratio, CO₂, or the relatively volatile elements on the right side of the periodic table. See Fig. 6-4, and pp.000-000.

120-
121 m.

Point: The zircon-baddeleyite reaction fixes the temperature of formation of tektite glass at around 1900°C.

Comment: In hot glass, this reaction takes place at temperatures which need not be higher than 1500°C (p.000).

ms p.88

Significance of lunar data

Point: Lunar glasses do not resemble tektites in chemical composition.

Comment: Most lunar glasses are basaltic. Basaltic volcanism is typically of the Hawaiian type, characterized by effusive flows, rather than the explosive type needed to propel tektites to the earth. Some sialic glasses from the lunar soil are not unlike tektites.

Point: Lunar rocks have higher Cr (up to 0.25 percent).

Comment: Similar Cr is seen in bottle-green microtektites (Glass, 1972b).

Point: Lunar rocks are generally richer in the refractory elements (Ti, Zr, Hf, and the rare earths).

Comment: Both lunar samples, as returned by Apollo and Luna projects, and tektites have been through a baking-out process, but it was more thorough for the material of the returned lunar samples than for the tektites. The difference may be a question of depth in the moon; the outermost parts may be poorer in volatiles.

Point: Lunar basalts have a peculiar pattern of rare earth elements, not seen in tektites.

TERRESTRIAL ORIGIN: ARGUMENTS IN FAVOR

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Comment: Apollo 16 anorthositic gabbros have a rare earth pattern which is very different from that of a mare basalt, and, in some cases, much like tektites (Taylor et al, 1972).

Point: Lunar rocks have ratios of potassium to uranium near 1000 to 2000; terrestrial rocks and tektites have K/U ratios about 10,000

Comment: Metzger et al (1973) find a variable ratio over the moon (by remote-sensing techniques); the ratio is particularly high on the far side, though it does not reach 10,000. The ratio measures volatilization, since K is volatile, while U is not; the ratio is not changed by most processes of magmatic differentiation. It is conceivable, as mentioned above, that the source region of tektites is a part of the moon which has suffered somewhat less differential volatilization than the lunar surface.

Point: Tektites could not be produced from lunar mare rocks by selective distillation.

Comment: This rules out origin by impact on mare rocks, as earlier suggested by me (O'Keefe, 1963b).

Point: Lunar basalts of the type called KREEP (rich in K, the rare earth elements, and P) are not like australites in chemical composition.

Comment: They are much more like the bottle-green microtektites; see Chapter 6, p.000.

Point: Rock 12013, whose major element chemistry is like certain javanites, is not glassy as stated by O'Keefe (1970a).

Comment: True.

Point: Discrepancies in the trace element composition of 12013 (as compared with tektites) are so serious that 12013 is not related to tektites.

Comment: Each new group of tektites to date has differed from the previously accepted definition of tektites in some minor way. Chapman (1971) thinks that 12013 belongs among the tektites, and particularly with the high-magnesium clan.

Point: Lunar sialic (granitic) rocks are generally higher by factors of 10 to 30 in K/Mg, and K/Na, compared to australites.

Comment: Australites are not the best comparison: moldavites are richer in K, and bediasites are much poorer in Mg. On the lunar side, Taylor took for his lunar sialic rocks the mesostasis (late-stage residual glass found between the crystals in basalts) or some immiscible globules found by Roedder and Weiblen (1970). These are indeed richer in K_2O and poorer in MgO than tektites. But in the lunar soils, there is a glassy

component (see p.000 and Table 6-6 which does not show the peculiarities of the mesostasis, and is much like microtektite glass. The abundance, in the fines smaller than 1. mm, is often between 1 percent and 1 per mil.

p.142MS

Point: Ages, especially ages of differentiation, so far found in lunar samples, are not below 3.2 b.y.; this suggests that the moon ceased to be volcanic some billions of years ago. Yet tektites have ages of differentiation which do not exceed 2 b.y., and at least some have ages under 50 m.y.

Comment: There is evidence, too complex to be given here, for rare contemporary paroxysms of lunar volcanism (see Chapter 10). If tektites are propelled by volcanism, their ages of differentiation would be expected to be near the ages of arrival at the earth's surface. The evidence seems to be reconcilable with this view (Chapter 7). The ages of arrival at the earth's surface are all relatively recent, because tektites have been found only in unconsolidated surface sediments.

Point: Lunar leads are radiogenic (high ratios of ^{206}Pb , ^{207}Pb , ^{208}Pb to ^{204}Pb). These indicate that the moon lost its lead at an early stage, and most of the lead now found there is due to the decay of uranium and thorium. Tektite leads, by

contrast, have ratios about a factor 10 smaller; and terrestrial leads are like tektite leads.

Comment: After the publication of Taylor's paper, it was found that some Apollo 17 leads are non-radiogenic; they are just about what would be expected for terrestrial or tektite leads at the date of the Apollo rocks, about -3.15 b.y. From this finding, both Tatsumoto et al (1973) and Silver (1974) concluded that the moon must have somewhere within its regions which contain more volatile elements than the material of most of the Apollo samples. If tektites are not terrestrial, they point in the same direction, as noted above.

Point: The oxygen isotope data on tektites does not fit the lunar oxygen isotope data, including that for specimen 12013.

Comment: As noted in Chapter 7, p. 000, the tektite oxygen isotope data is generally like that of terrestrial acid igneous rock ($\delta^{18}\text{O} + 9$ to $+11.5$ per mil.). Lunar oxygen is much like that of terrestrial basalts. Since 12013 contains a mixture of granitic and basaltic rock, in close proximity, there may have been equilibration.

Tektite oxygen isotope data, except that for Ivory Coast tektites and Darwin and Aouelloul glass, does not fit that of terrestrial sedimentary rocks.

Possible terrestrial parent material

Point: Tektites are not at all like any kind of basaltic or igneous terrestrial rock; and detailed comparison with granites excludes them also.

Comment: Tektites are most like intermediate rocks (andesites or dacites, for instance) except for a difference in silica content of the order of 10 percent. See Chapter 6, p000-000.

p. 119-1
120MS

Point: Variations in element ratios along the tektite sequence are not like those observed in terrestrial igneous rock suites.

Comment: They can plausibly be explained as igneous suites produced from magmas at low pressures (Chapman and Scheiber, 1969).

Point: Tektites are more like terrestrial sedimentary rocks than like terrestrial igneous rocks, especially in the rare earth elements.

Comment: In the major elements, it is principally the enhanced silica which produces a resemblance between tektites and certain sandstones. In the sandstones the cause is the high resistance of quartz to weathering. Some other cause must be responsible for the enhanced silica in specimen 12013, where it is combined, as in tektites, with high abundance of ferric oxides.

In the rare earths, the Henbury subgraywacke is only marginally closer to tektites than the standard andesite, AGV-1 (see Figs. 6-4 and 6-5).

Point: B.P. Glass (1970b) found chromite and zircon in Muong Nong tektites; these are very resistant minerals, characteristic of terrestrial sediments.

Comment: Finkelman (1973) found zircon and chromite crystals in the lunar soil; this soil also contained about 0.5 percent of glass resembling microtektites. Glass later (1970c) found rutile, corundum and monazite in Muong Nong tektites; of these, rutile was also found by Finkelman.

Point: Bottle-green microtektites might result from the melting of chlorite in a sediment.

Comment: Chlorite is rare in rocks which would yield a recent age of differentiation. It is characteristic of the metamorphic rocks of the basement complex, typically over 600 m.y. old. It contains over 10 percent water, thus making the fining problem one order of magnitude more difficult. Finally, the extreme bottle-green microtektites would have to start from rock that was 2/3 chlorite; such high concentrations are not typical.

Origin of tektites

Point: If tektites are produced by volcanic eruptions, then particles of tektite composition should turn up in lunar soils; but they do not.

Comment: The compositions of lunar granitic soil particles shown in Table 6-00 look like tektites. Material of this kind seems to form 0.1 to 0.5 percent of the fine fraction of the lunar soil. In a layer 10 meters thick, in which half the material is in the fine fraction ($200\mu\text{m}$ or smaller), the indicated quantity of tektite-like material is then 10 to 50 kg m^{-2} ; this is 4 to 5 orders of magnitude higher than the surface abundance of tektite glass in the Australasian strewn field. Clearly Taylor's statement is not justified in the present state of our knowledge. A thorough investigation of these granitic glasses is needed.

C.R.

Point: The Fe-Ni spherules found in tektites indicate meteorite impact.

Comment: The Fe-Ni spherules have been found only in philippinites (Chao et al, 1962), Dalat tektites (Chao et al, 1964) and Aouelloul (Chao et al, 1966a); this contrasts with their great abundance in true impact glasses.

Within the Australasian strewn field, the nickel abundance

averaged 9.1 percent in nickel-iron from Dalat (Viet Nam), but 2.9 percent in nickel-iron from Isabela in the Philippines. If there was a single impacting iron body, this result is unexpected.

The value of 2.9 percent nickel is exceptionally low for meteoritic iron; but Brett (1967) points out that in terrestrial impact glasses, nickel is almost always enhanced above the level in the impacting meteorite, because iron oxidizes preferentially and then dissolves in the surrounding silicate.

The Fe-Ni spherules are associated preferentially with the low-calcium high-aluminum tektite composition, both in the Philippines and in the spherule-bearing layer of Aouelloul.

The moon does have both endogenous and meteoritic nickel-iron spherules (Goldstein and Yakowitz, 1971) which do show a wide variation in nickel abundance; values below about 4 percent are classified as endogenous by these authors.

Point: Coesite (Walter, 1965) indicates meteorite impact.

Comment: The finding of coesite was difficult and should be confirmed. It does not seem to be present in all Muong Nong tektites. The peak shock pressures at which coesite forms correspond to Stage II and Stage III of von Engelhardt and Stoffler (1968). At these stages, unmelted feldspar is encountered, as well as melted grains which have not become mixed. Neither feldspar

nor glass of feldspar composition has been reported from Muong Nong tektites, although it is a necessary component of the hypothetical parent sandstone. Hence the coesite, if present, cannot have been formed by the same process as that which (according to the hypothesis of the terrestrial origin of tektites) made the glass.

Impacts of sufficient velocity to produce particles moving with lunar escape velocity should have melted the shocked rock, and very probably vaporized it.

Impact sites

Point: Ivory Coast tektites are established as coming from Bosumtwi crater.

Comment: The evidence is not convincing. The lead is young; Bosumtwi crater rock is old. The Rb/Sr age fit is forced. The K-Ar age fit was first announced as occurring at 1.3 m.y. (Zähringer and Gentner, 1963,); ~~Gentner et al., 1964~~; this was clearly a coincidence since the same authors later supported ages of 1.0 for the Bosumtwi and the Ivory Coast tektites; the possibility exists that the present agreement is also illusory. The chemical comparison is not precise; it is much improved if only Ata glass is used; but in this case the oxygen isotopes do not agree. No compositions corresponding to the bottle-green

microtektites have been reported around Bosumtwi.

Thus it premature to say that identity has been established between Ivory Coast tektites and Bosumtwi crater rock.

MISCELLANEOUS ARGUMENTS

Gases in tektite vesicles

Mueller and Gentner (1968) and Jessberger and Gentner (1972) have studied the composition of gases in tektites of the Muong Nong type. They find that the nitrogen and the rare gases in the vesicles of these tektites are unmistakably atmospheric (i.e. similar to the earth's atmosphere) in their abundance relations to each other and in the relative isotope abundances in each gas. They further find that as compared with the earth's atmosphere, the CO₂ is greatly enhanced (from the atmospheric value of about 0.03% to around 50% or more); while oxygen is depleted to values near zero. They conclude that the gas cannot be the result of leakage into the vesicles after the tektite solidified. They consider that the gas must have been trapped during an impact, when the oxygen had been consumed by fires, and the CO₂ had been released by the calcining of limestone.

This explanation neglects the kinetics of the problem. It is not possible to burn up a substantial log of wood in the second or

two of a meteorite impact, as a calculation of the thermal diffusivity will show and as common sense will confirm. Hence the only way to produce the CO_2 would seem to be to vaporize the vegetation, along with the rock, by shock. In the recombination process, the CO_2 might be produced from its elements. It is suspicious, however, that neither CO nor O_2 was left over; the constituents must have been present in very nearly their stoichiometric concentrations.

It is also curious that in the experiments with electrodeless discharges, in which there was no possibility of contamination since the vesicles were never broken, no trace was ever found of nitrogen or argon (O'Keefe et al, 1962) although the technique is very sensitive for both gases.

Gentner and his coworkers report that some of the vesicles are found to be void, in the same region where others have pressures of the order of 0.2 atmospheres ($2 \times 10^4 \text{ N m}^{-2}$). It is hard to imagine how the glass could have had sufficient viscosity to maintain a pressure difference of this kind, and at the same time permit the escape of the bubbles required to remove the oxygen (from the ferric-ferrous reduction) and the water. Under terrestrial gravity, the buoyancy forces are less than total pressure, in the approximate relation of the size of the bubble to one meter.

The existence of measurable even if small amounts of O_2 is hard to understand if the vesicles were sealed off while hot.

The equilibrium oxygen partial pressure in contact with tektite glass at 1200K is about 10^{-13} atmospheres.

It seems more reasonable to suppose that the vesicles which contain these gases were open to the atmosphere through very slow leaks. While the tektite was underground, it would be exposed, not to atmospheric air, but to soil air, which is rich in CO_2 and depleted in oxygen. If the leak was slow enough, the bubble could fill during the 700,000 years that it was underground, and not empty completely during the week-long outgassing employed at Heidelberg.

Muong Nong tektites and soil melting

Barnes and Pitakpaivan (1962) argued that the Muong Nong materials could be regarded as having originated by melting of the local soil. The soil is at present very different, being mostly Fe_2O_3 and Al_2O_3 like most laterites. Barnes and Pitakpaivan argue that it may have had a composition like a tektite before laterization. The argument is precarious, however, because the lateritic composition is a sink toward which soil compositions of all kinds - even limestones - trend as a result of strong leaching.

Urey (1963) and Barnes (1971c) regard the Munong Nong tektites as produced ~~in~~ place. However, the localities are up to 900 km apart, from a point 81 km west of Sakhon Nakhon (Barnes, 1963) to Bien Hoa, near Saigon (Fontaine, 1966) within S.E. Asia, and up to 2400 km if the Philippine site is counted (Barnes, 1964). Since these sizes are about 100 times larger than the sizes of comet nuclei, Barnes (1971c) suggested that they are produced by the comae of comets. Delsemme, however, points out (Barnes and Barnes, 1973, p.000) that the density of gases in the comae of comets is so exceedingly low that no mechanical effects of a collision of this portion of the comet with the earth is likely to be felt at the earth's surface.

C.I

Oxygen partial pressure

Walter and Doan (1969) calculated by extrapolation of their data that the oxygen partial pressure in tektites would not be far from equilibrium with the earth's atmosphere at 3000°C. On the other hand, the effect found by Brett (see Chapter 0) is direct evidence that the oxidizing properties of terrestrial sediments are much higher than those of tektite glass.

C.R

Mechanics of terrestrial impact

Arguments based on the mechanics of tektite formation are given in the next chapter, under the heading of arguments against the

terrestrial origin, because of the difficulties which they reveal in the hypothesis of terrestrial origin.

Formation of lechatelierite.

In his recent book, Rost (1972) offers a most important and fundamental argument against the volcanic origin of tektite glass. He notes that lechatelierite is usually present in place of quartz or cristobalite in tektites; and that in terrestrial lavas, it is not reported. On the other hand, he notes that Barnes (1958b) refers to the presence of lechatelierite in Pele's Hair, a volcanic product of Kilauea. The reference is to Baker (1944), who reports finding it. His finding has not had recent confirmation.

CONCLUSIONS

Tektites cannot come from beyond the earth-moon system. They are either terrestrial or lunar. Arguments against a lunar origin are therefore arguments for a terrestrial origin.

Tektites have more silica in their composition than would be expected from their content of ferric oxides. This is interpretable either in terms of terrestrial sedimentary processes (which may enhance quartz, as in sandstones) or in terms of lunar magmatic processes (as in sample 12013).

Tektites are more like terrestrial rocks than like most

returned lunar samples with respect to lead isotope abundances and rare-earth element abundances; they are more like terrestrial rocks than like any returned lunar samples with respect to potassium/uranium ratios and oxygen isotope ratios. It follows that tektites can be lunar only if there are places on the moon which contain more volatiles than the surface areas sampled during Apollo and Luna missions.

Hence it is very improbable that tektites are removed from the lunar surface by meteorite impact, which would be expected to hit the kinds of terrain which are commonest on the moon. Tektites must be either terrestrial or else the product of lunar volcanism.

A lunar origin for tektites is possible only if the lunar interior contains regions which are richer in volatiles than the areas sampled for the Apollo and Luna missions. The lead isotope data from Apollo 17 give some color of reality to this idea; but apart from these, the hypothesis of a relatively volatile-rich region in the moon is clearly ad hoc, and therefore somewhat lacking in credibility.

CHAPTER 9

THE TERRESTRIAL ORIGIN OF TEKTITES:

ARGUMENTS AGAINST

In this chapter, the arguments against the terrestrial origin of tektites are presented. In particular, the arguments concern themselves with the hypothesis of origin by meteorite or comet impact. No other theory of terrestrial origin has been seriously put forward, except by McCall (1973), since the discovery by Chao et al (1962) of nickel-iron spherules in philippinites. The chemical unity of the Australasian strewn field, from the western Indian Ocean east to Tasmania, and from Tasmania north to southern China, is evidence of origin from a single, relatively small region.. No matter where (on earth) this source region may have been, the size of the strewn field demands a velocity of launch of at least 6 km/sec, even if retardation by the atmosphere is ignored. This high velocity makes it difficult to believe in origin by terrestrial volcanic or cryptovolcanic explosions, as suggested by McCall, since the highest velocities for rocks from terrestrial volcanoes are believed to be about 600 meters per second (Sukhanov and Trifonov, 1974, p.154). Theory (Oswatitsch, 1956) says that gases escaping from a confining chamber into a vacuum will not exceed a limiting velocity which works out at about

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twice the sound velocity in the gas. For water at magmatic temperatures, this limiting velocity is about 2 km s^{-1} ; the needed 6 km s^{-1} is not physically attainable, unless the gas is heated to temperatures of $10,000^\circ\text{K}$ or higher; and this greatly exceeds any volcanic temperatures. Hence the terrestrial origin of tektites is usually taken as meaning origin by meteorite or comet impact.

The discussion in this chapter is arranged according to the sequence of events in the hypothetical impact: the area before impact; the formation of tektite glass in the impact; the launch from the impact crater; the passage upward through the atmosphere; the passage downward through the atmosphere; and the final arrangement of the strewn fields.

PROPERTIES OF THE IMPACT SITE

If tektites are produced by meteorite impact, then it is hard to understand why the bottle-green microtektites are found in the three strewn fields for which microtektites have been found, namely the Australasian, the Ivory Coast, and the North American strewn fields. The composition of the bottle-green microtektites can be described as pyroxenitic; but pyroxenites are not common rocks. Daly (1933) examined 159,000 sq.mi. ($412,000 \text{ km}^2$) of

geologic mapping in North America; he found 5.7 km^2 of pyroxenite, or a fraction amounting to about 1.4×10^{-5} of the total area. If one discounts the first occurrence of this material in the tektites, since any rock will have some peculiarity, it remains true that the chance of two successive further occurrences is 2×10^{-10} .

If tektites are the product of terrestrial meteorite impact, it is also puzzling that the particles of lechatelierite are persistently smaller than sand grains (Barnes, 1939). They average about 150×30 micrometers, and rarely exceed 1 mm in largest dimension, even when drawn out. Sand, on the other hand, is typically in the range of 200 micrometers diameter, ranging up to over 1 mm in diameter, even when it is approximately round.

THE GLASS-MAKING PROBLEM

As was shown in Chapter 6, the terrestrial material which most closely resembles tektites (chemically) is sandstone, such as a subgraywacke. Terrestrial igneous rocks, including almost all natural glasses, have the wrong composition. It follows that the production of tektites from terrestrial materials involves the formation of glass from rock which is not glassy, but consists of an aggregate of crystals. We are thus led to ask how glass can be made. We consider the process separately under the headings of solid, liquid and gaseous state transformations.

Solid-state transformation

Meteorite impact sometimes transforms crystals into glass by a solid-state transformation. The end-result is called a thetomorphic glass (Chao, 1968) or a diaplectic glass (von Engelhardt and Stoffler, 1968). In a thetomorphic glass, the original crystal boundaries are retained; even the internal structure of the crystal may survive. The shock of the impact has disordered the crystal just enough so that it has become optically isotropic. Tektites are certainly not examples of thetomorphic glasses; if the original material was indeed crystalline then nothing survives of the original crystal boundaries, with the doubtful exception of the lechatelierite particles.

Liquid-state transformation

A violent meteorite impact may deposit so much heat in the target material that the material is transformed into a glass by the normal action of temperature and time. Shock theorists call such glasses normal glasses (von Engelhardt and Stöffler, 1968). The transformation is accompanied by vesiculation (bubbling); there is flow, and the crystal boundaries are more or less completely lost.

The transformation of a sandy mass of crushed rock into a homogeneous and bubble-free liquid, which can then cool to what is ordinarily meant by glass, has been studied by glass scientists for

many years. Three principal steps are involved (Cable, 1969, 1970). These are melting, refining (eliminating bubbles - often called fining), and homogenizing.

Melting

As mentioned above, a violent shock can melt glass completely in a very short time. There is thus no obvious objection to the impact formation of tektites on this ground.

Refining

Terrestrial igneous rocks typically contain about 0.5 percent water; sedimentary rocks normally contain 1 percent water or more. Tektites, on the other hand, contain only about 0.01 percent water (see Chapter 6). If tektites are made from terrestrial materials, the water must have been removed somehow.

One obvious possibility is that the water is lost by diffusion. However, it turns out (O'Keefe, 1964c) that loss by diffusion is much too slow, even for rather small tektites, at temperatures which are unreasonably high. For example, 100 seconds are required for a tektite 6 mm in diameter at 3000°K .

In the production of commercial glass the volatiles are sometimes not eliminated at all; instead, the bubbles are eliminated by raising the pressure until they dissolve. This cannot be the way that tektites are made, because, as mentioned, the volatiles in tektites have been lost, not just dissolved.

When the volatiles must be eliminated, the only known way is to allow bubbles to form and rise to the surface of the liquid.

If tektites are launched by meteorite impact, then it is clear that the bubbles cannot escape during the very brief time when the tektites are being accelerated by the forces resulting from the impact. Whether these forces are due to shock or to gas pressure, they can only accelerate the tektite by pressure. But under pressure, the gases will not come out of solution. The amount of water in tektite glass is so small that in order to make it escape by bubbling, it is usually necessary to reduce the ambient pressure below atmospheric.

Following the launch phase, the tektites must move on a ballistic trajectory in free space from their origin to the point of fall. During this period, the pressure is low, and bubbles would be expected to form and expand. They would, in fact, be expected to convert the liquid to a foam, since the volume occupied by 1 gram of water at 1200°C and atmospheric pressure is 6600 cm^3 . In 100 grams of sedimentary rock, this steam would be accompanied by 99 grams of liquid rock, which would occupy a volume of only about 45 cm^3 .

The bubbles would not escape, however, because during this period the effective value of gravity is zero; hence they would

have no buoyancy. The problem of dealing with bubbles in a liquid which is in a ballistic trajectory is an important one whenever a liquid-fueled rocket engine must be stopped and restarted in orbit (Paynter, 1964). One must provide either a small "bottoming rocket" to accelerate the space-craft and so provide a g-force, or else one must comb the bubbles out with a mesh, or use some other ingenious device. None of these techniques appear applicable to the tektite problem, especially since tektite glass is exceptionally viscous.

The tektite will cool rapidly during the ballistic flight. Adams and Spreuer (1967) find that a sphere of diameter 2 cm will cool to the center in 100 seconds, at least in the sense that the central temperature will be below 1200°C , and hence the viscosity very high. The flight time exceeds 100 seconds for flights of only 65 km range (Hawkins and Rosenthal, 1962). Hence the gases cannot escape in flight.

It can also be shown (O'Keefe, 1964c) that regardless of the viscosity of the tektite, any program of acceleration which will force the bubbles to the surface will also reduce the liquid mass to a cloud of fine droplets. Both processes involve the same non-dimensional number (the Jeffreys number, equal to the ratio of the Reynolds number to the Froude number).

Friedman and Parker (1969) calculated the rate of escape of bubbles from liquid Libyan Desert glass. At 1600°C , they found that, under terrestrial gravity, escape through 2 cm of glass requires about 47 days. Note, however, that at this temperature, in a vacuum, the glass evaporates at the rate of $2.9 \times 10^{-5} \text{ cm s}^{-1}$. Hence the supposed 2 cm layer will evaporate in less than 1 day, or long before the bubbles escape. The same will then be true at all higher temperatures, because the activation energy for viscosity is slightly lower than that for evaporation, and hence the change with temperature is slower. (Note that Friedman and Parker's extrapolation to higher temperatures does not follow the Arrhenius law, for unexplained reasons.) This difficulty (being unable to fire the glass before it evaporates) is well known in the industrial production of silica glass (Winship, 1954).

As would be expected from these considerations, most normal (non-thetomorphic) glass from meteorite impacts is vesicular. Some (Chao, 1963^b) is dense, and has somehow retained most of its water. It is possible in principle at least that impact glass which is sufficiently densely buried in a layer of hot throwout should lose its volatiles by diffusion. But the hypothesis of the instantaneous formation of dense, water-free glass from ordinary sandstones, in material which has never been deeply buried, seems to be indefensible.

Homogenizing

The third problem of glass-making is that of homogenization.

The word glass can in principle mean any amorphous material; but in commercial glass it implies a material which is also homogeneous on a molecular scale; and tektites are glasses in this sense also. To reach this homogeneity demands diffusion, which is a slow process in viscous liquids. Numerical calculations require the coefficient of diffusion; unfortunately, in real glass-making problems, many components are simultaneously diffusing into each other, so that the concept of the diffusion coefficient loses its meaning. For some purposes, however, it can be replaced by the effective binary diffusion coefficient, a concept developed by A.R. Cooper. This can be applied, with some care, to give the rate of diffusion of a metal with respect to the glass as a whole.

Actual values of the effective binary diffusion coefficients for iron and for silicon in tektite glass were obtained by Varshneya (1970); these results are shown in Chapter 5. Varshneya and Cooper (1969) used the iron data to calculate the time required to homogenize the glass of a Thailand tektite. They concluded that even if the initial material was arranged in alternate perfect laminae, of iron-rich and iron-poor material, each pair of

laminae having a thickness of 40 microns, homogenization would not occur within a reasonable time (a second or so, for an impact).

Let us consider a more realistic case. A typical sandstone will have a framework of sand grains (Pettijohn, 1957), usually having a mean diameter greater than 125 micrometers. These will include grains of quartz (SiO_2), feldspar and other minerals. There should be not over 15 percent of fine-grained matrix, if the sandstone is a subgraywacke, as suggested by ^{S.R.} Taylor (1966). Pettijohn further finds that in the range of 125 micrometers, over 90 percent of the grains are monomineralic (composed of a single mineral).

We suppose the whole mass to be shock-melted. Then the dissolution of the quartz grains (for example) demands diffusion of silicon through distances of the order of 1 grain diameter as a minimum.

But this is not enough, because even after the grains have disappeared, the resulting mass will be inhomogeneous because of statistical variations in the relation of quartz to the other constituents in the initial sandstone. We can consider the problem as if the effect of diffusion were to average the composition of all the grains in a certain volume. Suppose the volume contains 100 sand grains. If we calculate the normative mineral composition by the standard methods, we find 45 percent quartz and 55 percent of other minerals.

Then on the average, 45 grains out of the hundred will be quartz.

The actual number expected is given by the binomial distribution, whose standard deviation σ is given by Fry (1965, p.222)

$$\sigma = \sqrt{mp(1-p)}$$

where m is the number of grains, and p the fraction of quartz grains.

We find at once that σ is very nearly 5.

Hence if diffusion takes place only through batches of 100 grains or so, then we can expect a standard deviation of the silica content which will correspond to adding or subtracting 5 quartz grains to the mean value of 45. Since there is about 50 percent silica in the non-quartz grains, this works out to a standard deviation of 2.5 percent in the total silica content.

In fact, however, the graphical presentations of Walter (1965) show that the standard deviation of the silica content even in a Muong Nong tektite is only about 1 percent. Hence if tektites are the result of the melting of sandstones, we must consider that diffusion takes place through larger volumes; with 1000 grains the expected standard deviation is reduced 0.8 percent, which is a reasonable approximation to the observations of Walter.

It follows that diffusion is called upon to reduce the irregularity in composition in a sphere of diameter 1.25 mm (i.e. 1000 grains of diameter 125 micrometers) to, say, $1/e$ of the

original amount; we next show that this demands an excessive time.

As usual in calculations of diffusion, we make use of the fact that the diffusion of matter is mathematically like the diffusion of heat. From the thermal calculations of Carslaw and Jaeger (1959, p. 234), we see that the diffusion into a sphere requires that

$$\frac{Dt}{a^2} \geq 0.2$$

where D is the diffusion coefficient, a the semidiameter of the sphere, and t the time. Substituting $D = 3 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ from the curves of Varshneya (Chapter 5), for 1800°C , and $a = 0.062 \text{ cm}$, we find that a time of $2.6 \times 10^4 \text{ s}$, or 7.2 hours would be required for homogenization.

It might be imagined that the process of homogenization could be aided by mixing. The effects of mixing can indeed be very powerful in speeding-up homogenization. Consider, for instance, a rod of glass, divided lengthwise into a red half and a green half. If the rod is now heated, stretched and folded in two, and reshaped, it will have two red and two green stripes. If we stretch and fold again, there will be four of each, and so on. After 20 steps, the separate red and green portions are reduced to a millionth of their original thickness.

Something of this nature, though not nearly as effective, clearly occurred with many splash-form tektites, in which the

lechatelierite particles are drawn out into filaments 20 times as long as they are thick.

The data on homogeneity quoted above from Walter (1965) is for Muong-Nong type tektites, however; in these, the lechatelierite particles are nearly equant (i.e. have nearly equal diameters in all directions) and lack the long tails of the lechatelierite in the splash-form tektites. It follows that we cannot explain the homogeneity of the Muong Nong tektites by a mixing process.

Further evidence against mixing in the Muong Nong tektites is furnished by the layering, which is usually not strongly contorted.

If the temperature in the Muong Nong tektites had been very high, then the diffusion could have occurred more rapidly. On the other hand, Walter (1965) reports crystalline quartz and coesite in the same material as that used for the study of homogeneity. Temperatures above 1800°C would destroy both minerals in a few minutes or less. Similarly the presence of other crystalline minerals in tektites (Glass, 1970c) speaks against high temperatures.

Finally the spinous voids (see Chapter 4) found in many Muong Nong tektites would collapse into spheres or ellipsoids because of surface tension if Muong Nong tektites had ever been soft. O'Keefe (1966b) calculated that the time required for homogenization would be approximately 10^7 times greater than that

required for the collapse of the spines. Since the diffusion time is roughly proportional to the viscosity, by the Einstein-Eyring relation, it follows that his discrepancy cannot be removed by altering the assumed temperatures.

From the experimental point of view, Varshneya and Cooper (1969) heated one artificial tektite batch for 24 hours at 1550°C ; it still had bubbles. Another batch was heated at 1550°C and then had a 4-hour soak at 1800°C ; this batch was bubble-free. Neither batch was as homogeneous as a Thailand tektite.

Note that in a vacuum the tektite would evaporate in 4 hours at 1800°C . Moreover, the activation energy for iron diffusion is much below that for vaporization (64kcal/mol vs 180) and hence vaporization would, in a vacuum, precede homogenization at all higher temperatures.

In short, the idea of producing homogeneous glass by instantaneous heating of natural sandstones fails by many orders of magnitude.

Transformation in the gaseous state

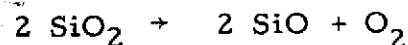
Could tektite glass be formed by evaporation and recondensation? Something of this kind occurs in an atomic explosion, in which large quantities of silicates vaporize and then condense. The process could well be imagined to eliminate water and argon, and to result

in a homogeneous glass.

The difficulties in accepting this idea are as follows:

(a) When silica is evaporated and then recondensed, the result is not stoichiometric SiO_2 unless the process is carried out very slowly, at the lowest possible temperatures. Hass et al (1969) describe the evaporation and recondensation of SiO_2 ; use is made of an electron gun, defocussed to avoid overheating and decomposition. Films so produced are transparent; but if evaporation is done using a focussed beam, or a directly-heated boat of some refractory material, then the deposited film is overheated and decomposed. Non-stoichiometric silica has strong absorption bands, especially to the violet of 450 nm (Cox et al, 1964). Sinclair and Peters (1963) describe similar techniques, and note deposition rates of 7.5 nm per minute. To build a layer one centimeter thick at this rate would require several years.

The basic difficulty is that in the gaseous form, silicon dioxide decomposes:



The equilibrium constant is given in the JANAF Tables (Stull and Prophet, 1971); in the presence of atmospheric oxygen the ratio of the two molecules is as in Table 9-1. Serious

decomposition of SiO_2 sets in above 1400°K . Clearly, if allowance is made for the very low P_{O_2} found by Walter and Doan (1969) the ratio of SiO/SiO_2 will be still higher.

The blackness and opacity of non-stoichiometric silica is in obvious contrast with the optical properties of Libyan Desert glass and the Georgia tektites and moldavites.

(b) The recondensation process would be expected to begin with the more refractory oxides, and end with the most volatile. As a result, it would be expected that the microtektites would have an outer coat rich in the more volatile oxides. Such coats (rich in lead and iron) are actually observed on atomic fallout (Norman and Winchell, 1966); but nothing of this kind is seen in tektites, although it has been looked for (B.P. Glass, personal communication).

(c) It is essential to the hypothesis of terrestrial impact that the tektites should be distributed by expanding gases formed during the impact. But the gas expansion itself insures that lumps of condensing glass will not grow to large size (compared to nuclear fallout, i.e. microgram size) before the cloud becomes so dilute that growth ceases (Stewart, 1956).

(d) The Muong Nong tektites in particular possess a horizontally layered structure, which probably formed on some planetary surface, because there is a definite orientation of the

vector of remanent magnetism with respect to the layering, and because there is evidence of welding of small particles. The welding could not have taken place after the arrival of the glass at the surface of the earth, because Muong Nong tektites, like other tektites, are never welded to true terrestrial materials (such as sand, loam, or crystalline rock of the earth).

Observations of impact glass vs tektites

From the observational standpoint, it is indeed found that tektites differ from impact glasses in that they are more homogeneous and less vesicular, and that the dense impact glasses have not lost their water content. These points were brought out by Chao (1963b); and indeed the above discussion of the glass-making problem can be considered as no more than an attempt to provide a theoretical foundation for Chao's observations.

The instantaneous production of substantial masses of homogeneous and relatively bubble-free glass from common soil and rocks is not physically comprehensible, and has not been observed.

ARGON LOSS

As pointed out in Chapter 7, the process of expelling argon from tektite glass is extraordinarily difficult; it demands, in effect, the complete volatilization of the tektite. It does not seem plausible

that the argon could be expelled in a terrestrial impact in a matter of a second or two. But if this cannot happen, then why do tektites yield good K-Ar dates? Shock alone has little effect on the argon distribution; it is well-known that in lunar rocks the K-Ar dates are always very old, although at least some lunar rocks must have been recently shocked by impact.

DEFICIENCY OF VOLATILES

As compared with terrestrial rocks, tektites are systematically deficient in elements which are volatile at temperatures of 1000°C and below. This point was noted in Chapter 6. The deficiency is qualitatively similar to the deficiency noted in lunar rocks. Comparison of terrestrial impact glasses with their parent rocks (Taylor, 1966, 1973) shows no similar pattern of loss.

LAUNCH PROBLEMS

One of the great surprises of the Apollo and Luna programs was the finding that the impact of meteorites on the moon has sent no identifiable materials to the earth. No meteorite and no tektite found on the earth's surface corresponds in composition to the typical lunar rocks of the maria and the highlands. Anders et al (1971) remarked, in their study of Apollo 12 material, that

"the now-established absence of lunar rocks in the world's meteorite collections apparently rules out an origin from larger bodies (Mars, Mercury, etc.) because ejection of rocks by impact is apparently very improbable even for the moon, whose escape velocity is as low as 2.4 km s^{-1} ." Of course no one knows whether meteorites or tektites correspond to some rare class of lunar rocks; but to establish Anders' conclusion it is enough to say that they do not correspond to the common types of lunar rock. Ejection, unlike volcanism, is a random process.

The above conclusion, that impact cannot produce velocities over 2.4 km s^{-1} , is strengthened when we note the rarity of the petrographic marks of shock in the large rocks of the lunar surface. In the soil, on the other hand, shock is relatively common.

Again, at any point on the moon it is found that the decimeter-sized specimens are all of a single type, or a small range of types. These are believed to be the same as the underlying rock, although bedrock was seen only in Apollo 15. The range of rock types was much larger in the soils. Even among the soils, however, it was uncommon to find particles which had clearly been sent long distances by impact. Exotic particles tended to belong to a few types, such as the green glass spherules, or the orange spherules, for which the possibility of volcanic activity could not be ignored.

The underlying cause for this failure to eject particles with high velocity from impacts has been discussed by Opik (1958).^b

In a shock, there is an unavoidable connection between shock pressure p and shock velocity w , of the general form

$$p = C\rho w^2$$

where ρ is the density and C is a dimensionless constant of the order of 1. As soon as the velocities approach the lunar escape velocity, the corresponding pressures approach 20 billion N m^{-2} , or about 200 kilobars. A rock can survive a pressure of this size if it is confined on all sides; but in that case it cannot be launched. If it is to be launched, the pressure must be one-sided; then the rock will be crushed to powder.

If the pressures are a little higher, the rock will be liquefied and sprayed. It will not be launched either as a solid mass or as a gob of considerable size.

Evidently, if impact cannot produce velocities of 2.4 km s^{-1} or larger, it is still less likely to produce the 4 km s^{-1} required to explain the North American strewn field, or the 6 km s^{-1} necessary to explain the Australasian field, even in the absence of atmospheric resistance.

Many tektites have obviously been shaped by surface tension, or forces no stronger; this is indicated by their external shapes,

and made certain by the presence, in some tektites, of internal bubbles which are nearly spherical and approach a centimeter in size. Such an object would be destroyed, literally, by a breath (Chapman and Larson, 1963). A terrestrial impact event capable of launching the object at 6 km s^{-1} would necessarily involve one-sided pressures of about half a megabar ($5 \times 10^{10} \text{ N m}^{-2}$).

It was suggested by Lin (1967) that this argument of Chapman did not take into account the effects of viscosity. However, we note that the high pressures come when the tektite is hot; if it is sufficiently viscous to resist deformation at this time, then it turns out from a numerical analysis that it cannot be sufficiently fluid later on, when cooler, to yield to surface tension (O'Keefe, 1963).

UPWARD PASSAGE THROUGH THE ATMOSPHERE

Even if a tektite were to be launched upward at the very high velocity demanded to reach the outer parts of the strewn field, it could not penetrate the undisturbed atmosphere. It is well known that meteorites weighing less than several hundred tons always reach the earth with terminal velocity (a few hundred meters per second or so) rather than with their velocity in space (not less than 11.2 km s^{-1}). This point was first made by Nininger (1943b); later it was discussed by Chapman and Larson (1963), and Adams (1963).

Lieske and Shirer (1964) calculated atmospheric trajectories for tektites; a one gram tektite moving at 11.2 km s^{-1} will be arrested after 360 meters of flight at surface atmospheric density.

The basic problem is that a tektite moving through the atmosphere is preceded by a shock wave, also traveling at a speed of, say, 25 times the velocity of sound. Behind the shock wave, the air moves with subsonic velocity with respect to the tektite. This means that with respect to the ground, the mass of air, dM , behind the shock, has got within a few percent of the velocity, V , of the tektite. The momentum which it has gained, namely VdM , must equal the momentum lost by the tektite, namely $-M_0 dV$, where M_0 is the mass of the tektite:

$$VdM = -M_0 dV$$

Let V_0 be the initial velocity of the tektite, and V_s the velocity of sound; then

$$\frac{1}{M_0} \int_{V_0}^{V_s} dM = - \int_{V_0}^{V_s} \frac{dV}{V}$$

The integral on the left is approximately the column integral of the air mass encountered by the tektite; call this M_1 . Then

$$M_1/M_0 = \ln \frac{V_0}{V_s} \approx 3$$

i.e. the tektite will be reduced to terminal velocity when the column integral of the air encountered is about 3 times its own mass.

For a tektite with a frontal area of $1 \text{ cm}^2 (10^{-4} \text{ m}^2)$ passing vertically

through the atmosphere, this integral is close to 1 kg; it is thus hundreds of times too large to be overcome by the tektite's momentum. The derivation is not precise, but it makes clear the fact that the difficulty is not some aerodynamical subtlety, but is a manifestation of Newton's Third Law, plus that fact that air pressure on the rear surface of the tektite is negligible at hypersonic speeds.

The whole problem is, of course, made 2 orders of magnitude more difficult by the finding that microtektites cannot be explained as ablation products of macrotektites; they seem to have arrived as separate bodies.

In reply to these arguments, Cohen (1963) suggested that the explosion resulting from the impact produced a local vacuum, through which the tektites penetrated the atmosphere. Lieske and Shirer (1964) replied that the partial vacuum so produced would still have a density so high as to stop the tektite; further, they noted that the blast wave is not likely to penetrate the whole atmosphere.

Hawkins et al (1964) offered an ingenious solution to this problem. They suggested that the dust and rock from the explosion, which should greatly outweigh the melt, would burst through the atmosphere and open a path for the tektites by driving the air before them. If this explanation were correct, then the tektites should have been accompanied by large volumes of dust and sand. On land, of course, these deposits might well be unnoticeable. B.P.Glass

tested this idea by making counts of sand grains in a core which also contained microtektites. The results are shown in Fig. 9-2; there is no increase in sand near the time of microtektite arrival; hence this idea, which deserves more attention than it has had, does not work. It seems probable that in any kind of terrestrial impact there should have been great masses of partly fused rock; but nothing is noted in the oceanic cores.

The problem was further discussed by Lin (1966), who considered that the air might move along with the tektites. Lin perceived that if the tektite outruns the blast wave from the impact, it will reach undisturbed air, and will be stopped, as mentioned, unless the air is of very low density.

The velocity of a shock wave

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(unlike that of a sonic wave) depends on the strength of the shock; it diminishes in proportion to $r^{-3/2}$, where r is the distance from the explosion. However, for the part of the shock wave that goes vertically upward, there is a counteracting influence; a negative density gradient increases the shock velocity. For an explosion which greatly exceeds 2×10^{17} joules (i.e. 50 megatons TNT equivalent) the atmosphere blows out at the top for this reason. This blowout is necessary for the escape of tektites into ballistic orbits in empty space. The critical energy Lin designated E^* .

no
← space
here

However, matter rising vertically from the impact cannot be expected to contain solid or liquid particles; there will be only gases from the impact. Hence, Lin argued, the only explosions capable of launching tektites are those which are so violent that the gases move outward horizontally (so that they can entrain surface matter). Because of the curvature of the earth, the waves which start out at a tangent to the earth's surface eventually escape into the very high atmosphere; the tektites entrained can go on into space. The energy demanded is $10^6 E^*$, or 2×10^{23} joules. The corresponding crater dimensions, using the theory of Bjork (1961) are 300 km diameter, and 40 km depth.

Lin's paper was discussed further by Chapman and Gault (1967a).

After making a number of corrections, they concurred that an explosion of the type contemplated by Lin, producing a crater 280 km in diameter, would be capable of ejecting solid matter into space. They pointed out that the Ries crater is about 10^3 times too small, and Bosumtwi about 10^4 times too small; they felt that it was doubtful that such a huge crater as required could be concealed anywhere on earth.

Lin (1967) replied that the mechanism which he had discussed was not applicable when the range was as short as that from Bosumtwi to the Ivory Coast tektites (300 km to the grouping near Ouelle known at that time) or from the Ries to the moldavite strewn field. Glass (1968) showed, however, that the Ivory Coast strewn field extends to a distance of 1600 km from Bosumtwi when he found microtektites off the coast of Liberia which were later shown to be chemically part of the Ivory Coast strewn field. The density of microtektites in this single ocean core and the indicated size of the field are such that a simple calculation suggests that the total mass of the Ivory Coast strewn field is not necessarily significantly inferior to that of the Australasian strewn field (Glass, personal communication).

For the North American strewn field, Glass et al (1973) find that the suggested mass, on the basis of four cores, comes out three orders of magnitude greater than that of the Australasian strewn field.

It is thus hard to accept the hypothesis of the terrestrial origin of tektites if we believe Lin's theory. It seems to call for two Pleistocene craters, of which one at least has an area about like Ireland, and a volume about like the land surface of Antarctica above sea level. In addition, a third crater, of Tertiary age, is called for which was 10^3 times as effective in producing tektites. Craters of this size and this recency ought to be discoverable.

A somewhat different theory for terrestrial origin has been developed by E.J.H. David (1966a, b, c, 1967a, b, 1969, 1972). David notes that the physical evidence precludes a slow cooling process for tektite glass, and concludes that the shock produced by the impacting meteorite could not have left much residual heat in the tektites. Since shock processes normally leave behind something like half the heat developed at the peak of the shock, David chose a theory which depends on not shocking the tektite material. He considers that the source material was the layer of compressible soil just at the surface of the earth. Because of its softness, the effect of impact pressure was not to shock the soil, but to produce isentropic compression (i.e. compression without change of entropy, and hence reversible). During the subsequent expansion, the heat produced by the compression is turned back into mechanical energy; i.e. the process is efficiently reversed. This could happen only

in the very thin zone between the shock wave which propagated downward into the earth and that which propagated upward into the meteorite. His calculated pressures go up to about 8 megabars. ($8 \times 10^{11} \text{ N m}^{-2}$) and are released after about 100 milliseconds.

It is essential to this theory that tektites be made from the top meter of the earth. For a total mass of 10^{11} tons, as required for the North American strewn field, a circular area of $5 \times 10^{10} \text{ m}^2$ must be stripped; this means that the impacting asteroid must have had a diameter not less than 250 km, equal to one of the four largest asteroids (Juno). The crater which would be excavated would have a diameter approaching 1000 km (Chapman and Gault, 1967a). This is an unreasonable size for a Tertiary crater in North America of which no trace can be found.

David's theory was constructed before the mass of the North American strewn field was known. Even at that time, however, he very properly pointed out that the derivation of tektites from terrestrial impacts required an "a priori incredible process" which could be justified only by what he felt to be the weight of the geochemical evidence. It is for this reason that the discussion of physical theories of tektite formation has been postponed to the chapter on arguments against the terrestrial origin of tektites.

Vand suggested (1966) that tektites were formed by jets of

liquid material which resulted when a cavity in the earth (formed by the arrival of a meteorite) collapsed after the impact. The jet would have enough mass back of each square centimeter of frontal area to drive through the atmosphere. It would explain, he felt, the strewn fields like the moldavite strewn field and the Ivory Coast strewn field, which subtend only a small angle at the initial crater.

This idea was considered by Adams (1965) who showed, from considerations of hydrodynamics, that such a jet would necessarily be strongly retarded; to reach a height of 200 kilometers with a velocity of 1 km s^{-1} an initial velocity of 74 km s^{-1} is necessary. Moreover, the jet breaks up into droplets which are themselves destroyed. Finally the jet sheds liquid drops all along the line over which it passes.

Adams further found that the jet could not go back into the hole in the atmosphere made by the incoming meteorite because this hole would close up promptly as a result of the heating of the air.

STREWN FIELD GEOGRAPHY

If tektites were the result of terrestrial impact, it would be expected that they would be arranged in streaks radiating from the crater of origin. Near the crater of origin, one would expect a greater abundance of tektites.

In fact, in the Australasian strewn field, the streaks are subparallel to one another (Fig. 2-8). They do not radiate from any point within the strewn field, nor is there any conspicuous concentration anywhere.

In the moldavite strewn field (Fig. 2-11) there is a distinct suggestion of two parallel streaks of slightly different composition, running NW-SE, i.e. nearly perpendicular to the direction to the Ries crater. The impression is reinforced by the fact that in each region, the heaviest tektites are at the NW end of the streak. The new tektites found at Prague support this pattern.

Although Vand (1966) suggested that the moldavites are the locus of a jet from the Ries, there are no moldavites near the Ries. The new Prague tektites increase the angle subtended at the Ries from 15° (Cohen, 1963) to 26° , which weakens the concept of the field as a single radial splash from the Ries.

Similarly the finding of tektites in the sea off the Liberian coast increases the angle subtended at Bosumtwi by the Ivory Coast strewn field from 12° (Cohen, 1963) to 45° .

DOWNWARD PASSAGE

The pattern of ablation observed on flanged australites is found (Chapter 3) to imply entry velocities greater than those expected for objects flying from point to point on the earth. The pattern is consistent with velocities in the range of 8 km s^{-1} only if the angle of entry is very nearly horizontal, and if we set aside the evidence from ring-waves and flange shapes, and from the thickness of the zones affected by heating.

It has been informally suggested from time to time that the same ablation phenomena might be produced by gases blowing upward past a tektite, and so accelerating it to its flight velocity. But Chapman et al (1962) showed that australite shapes are stable only if the australite is in descending hypersonic flight, i.e. flight in the direction of increasing density. If moving in the direction of decreasing density, australites would be expected to tumble so that there would be no difference between the anterior and the posterior sides.

The credibility of the re-entry theories which are being used here is enhanced by the fact that more or less similar theoretical studies underlie the heat shields in use for many missiles and spacecraft. Over the past 15 years, these theories have been confronted with reality on many occasions; their success is well known.

The downward passages of tektites other than australites are still not understood. Chen considers (unpublished communication) that these can be explained in terms of the same velocities as those now used for australites; the difference may lie in the roughness of the bodies and their resultant tumbling.

CONCLUSION

The Comte de Fourcroy (Fourcroy, 1804), considering the evidence for the cosmic origin of meteorites, remarked, "In such a question, one is compelled to choose between ideas which are just as unprecedented, the one as the other; and it is only by eliminating the absurd or the impossible that one is forced to accept what would at first have seemed almost unbelievable."

It is absurd to suppose that impacts of large objects take place preferentially on very rare pyroxenite rocks, or that the earth has a number of undiscovered Cenozoic craters larger than Ireland, or that the standard re-entry calculations contain gross errors leading to underestimates of the ablation. It is impossible to make glass of good quality, devoid of water, instantly from common rocks and soil, or to drive argon out of tektite melts instantly, or to launch megascopic particles at 6 km s^{-1} by shock, or to penetrate the atmosphere with gram-size bits of glass at hypersonic velocities.

We are thus forced to accept the conclusion, which at first seems incredible, that tektites, despite their remarkable resemblance to terrestrial rocks, do not originate on the earth. .

CHAPTER 10

CONCLUSIONS

From this study of the tektite problem, a number of conclusions can be drawn; clearly they are of widely varying certainty. The conclusions fall under four main headings:

- (1) The origin of tektites
- (2) The structure of the source volcano on the moon
- (3) The moon's origin
- (4) Implications for the earth

ORIGIN OF TEKTITES

We proceed from the conclusion of Chapter 9, that tektites cannot be terrestrial in origin. Then they are probably a kind of lunar obsidian; that is, they are volcanic ejecta, of geologically recent epochs, from one or a number of lunar volcanoes. The steps in the argument are as follows:

Tektites as volcanic rocks

It seems very likely that tektites are the result of volcanic processes rather than of melting by impact. Of the arguments given in Chapter 9 against origin by meteorite (or comet) impact on the earth, a number are also applicable to impact on the moon.

In particular, it is now clear that sites on the moon having the proper chemical composition for tektites are quite rare; tektites are chemically different both from the rocks of the lunar maria and from those of the uplands. This eliminates an impact origin from the moon, though it does not eliminate a volcanic lunar origin.

Of the glass-making problems mentioned in Chapter 9, it is true for the moon as for the earth that tektites cannot be made by solid state transformations nor by evaporation and condensation. The problem of homogenization in the liquid state is just as serious on the moon as on the earth; it implies that the formation of tektite glass must have required times of heating much longer than those involved in impact.

The problem of launching tektites from the moon by impact is not quite as insoluble as launching from the earth; the required velocity is only 2.5 km s^{-1} instead of 6. Nevertheless, as noted in Chapter 9, it appears that impact does not get macroscopic particles up to this velocity.

It seems to follow that tektites must be volcanic rather than impact glasses, wherever they come from.

Tektites as lunar volcanics rather than terrestrial

As noted in Chapter 6, tektites are systematically different from terrestrial volcanic rocks; they are dryer, lower in ferric-ferrous ratio, and contain less volatile elements. These differences are all in the direction of lunar materials. They have been considered to exclude terrestrial volcanics as the source of tektites since the 1920's.

In addition, origin from terrestrial volcanoes is subject to some of the objections brought forward in Chapter 9 against terrestrial impact. There is no reason to believe that terrestrial volcanoes can furnish sufficient velocities; the limiting velocity (Oswatitsch, 1956) for steam at magmatic temperatures (around 1200°C) is about 2.4 km s^{-1} , while 6 km s^{-1} is needed. The upward passage through the atmosphere is impossible unless the atmosphere is removed; the pattern of the strewn field does not fit; and the ablation evidence indicates velocities inconsistent with origin from any terrestrial source, especially one that can furnish maximum velocities around 2.4 km s^{-1} .

We are thus led to the conclusion that tektites are the ejecta of lunar volcanoes. In a way, this conclusion is a very natural one: most of the early students of tektites thought they were obsidians. Charles Darwin, for instance, ⁽¹⁹⁴⁴⁾ thought his

australite was a volcanic bomb. Likewise all Australian workers up to 1898 referred to australites as obsidian bombs; Dunn (1935) held out for this idea for forty years. Van Dijk (1879), the discoverer of the billitonites, called them obsidian; Josef Mayer (quoted in Suess, 1900) remarked that moldavites appeared to be a sort of glassy lava; and Breithaupt, in 1823 (quoted in Suess, 1900), specifically referred to moldavites as obsidians. The realization that all of these three peculiar obsidians should be classed together was due to Verbeek (1897a, b); he was also the first, in these papers, to suggest that they were the ejecta from lunar volcanoes. Where tektites and obsidians occur side by side, as in the Philippines, there is serious danger of confusion, fortunately cleared up by Koomans (1938). Similarly La Paz (1948) showed that the valverdites were not tektites but weathered obsidian pebbles; and Heide (1936a) showed that the macusanites were not tektites but a kind of volcanic glass.

From the modern standpoint, one immediate objection to the hypothesis of significant contemporary lunar volcanism is the fact that, despite a comparable rate of heat generation, the moon's seismic activity is about 10 orders of magnitude below that of the earth. No volcanic eruption of any size can have occurred anywhere on the moon since the first seismometer was

established there in 1969. Many workers feel that the moon has been devoid of volcanic activity since the flooding of the mare basins at -3 to -4 b.y.

But gases are accumulating in the moon as a result of radioactive disintegration. If we assume that the present abundance of K in the moon is about 1000 ppm, then the accumulated production of radiogenic ^{40}Ar since -3 b.y. amounts to approximately $1/2$ ton per m^2 of the lunar surface. Of this, according to Hodges et al (1973), only about 0.4 percent is escaping by steady flow. Since the moon is not balancing its gas budget on a day-to-day basis, the potential for colossal volcanic eruptions exists even if all volatiles were lost at -3 b.y.

• If we keep in mind the fact that below 1000 km, the lunar interior seems to be at least in part molten (Nakamura et al, 1973), then there is, at least on the face of it, a case for contemporary lunar volcanism. It must be sporadic, or it would show on the seismograms. The idea of such activity is more plausible, in some ways, than the idea that the ratio of seismic activity to heat flow on the moon is truly 10^{-10} that of the earth, even over the long run.

CONCLUSIONS

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THE SOURCE VOLCANO

In this section, we shall assume that a single volcano is the source of tektites. It may in fact be true that there are several, but the number is certainly quite small. We shall try to estimate its period of activity, location, total output, gases, ejection velocity, morphology, source depth and behavior.

It may seem pointless to try to give a description of a volcano whose mere existence is highly controversial. But by working out its characteristics, we test the idea to see whether it is self-contradictory. We also provide answers to critics who say that a lunar volcano could not function as proposed. We stimulate the observers to test these ideas.

Finally, if tektites are lunar, then the fact is not at all "terminal," in Urey's phrase; i.e. it has implications for all our ideas about the moon, and even the early earth. The usefulness of the study of tektites is best demonstrated by working out the consequences of the results which have been reached.

Period of activity

The simplest explanation of the radioactive dates noted in Chapter 7 is that the K-Ar, Rb-Sr, and U-Th-Pb dates for a given strewn field all refer to the same event. Then the dates of the strewn fields correspond to the periods of activity at the corresponding vents.

In the case of the Australasian strewn field, it is possible that the eruption which occurred at $\sim .75$ m.y. carried with it some products of earlier eruptions. This might explain the high-sodium tektites with their ~ 4 m.y. dates.

It would also help to understand the Muong Nong tektites ~~if~~ if there had been several eruptions within a short period of time. The Muong Nong tektites have some fundamental resemblances to terrestrial welded tuffs. This would imply that there had been earlier eruptions at the same site, which had deposited hot microtektites near the vent. The more acid microtektites welded, under the pressure of overlying deposits, to form the Muong Nong layered tektites. These were then torn loose in a subsequent eruption, perhaps only a few thousand years later, and sent to the earth along with the rest of the Australasian tektites.

So far, tektites are known only from the latter part of the Cenozoic. It would be possible for a very dry glass such as a tektite to resist devitrification for billions of years, as is seen on the moon. Hence the failure to find earlier tektites is puzzling, especially since the larger strewn fields have been repeatedly rediscovered (e.g. the Australasian strewn field, which was independently discovered in Australia, Billiton, the Philippines, S. China, Viet Nam, Java, Borneo, the South China Sea, and as

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microtektites in deep-sea cores; the North American strewn field, discovered in Texas, Georgia, Massachusetts, Cuba and the deep-sea cores; the Ivory Coast strewn field on land and in the cores; and the moldavites in Bohemia and Moravia). Very few discoveries of tektites have resulted from conscious searches; almost everywhere, discovery has amounted to the recognition that something already found is a tektite.

These facts suggest that our list of tektite strewn fields may be reasonably complete. If so, the source volcano did not become active until the latter part of the Cenozoic.

Location

The moon's orbital velocity averages about 1.02 km s^{-1} .

If a stone is thrown from the moon with just enough speed to escape the moon's attraction, the stone will still possess this orbital velocity, and will go into a nearly circular orbit around the earth, like the orbit of the moon; then it can never come near the earth. To hit the earth, it must have, in addition to its escape velocity, a component of motion with respect to the moon which will cancel the moon's orbital velocity. Hence the source crater is probably on the moon's eastern hemisphere (which is the side opposite the direction of the moon's orbital motion).

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Shute (1966) has made an important simplification of the problem of moon-earth trajectories. She notes that objects leaving the moon are moving in hyperbolic orbits with respect to the moon's center of mass. At large distances from the moon, the orbits approach their asymptotes. To a certain approximation, the asymptotes can be replaced by straight lines emerging from the center of the moon; the error in direction approaches zero asymptotically, and the error in lateral displacement is generally of the order of the moon's radius, i.e. a few thousand kilometers. The lines from the center can be described in terms of their intersections with a sphere. If the sphere is taken at a distance of, say, 10 lunar radii from the center, then the intersection of the actual orbit of the object with this sphere will be not far from the intersection of the radial line with the sphere. It follows that we can substitute the latitude and longitude of the intersection of the orbit of the particle with this sphere - the Shute sphere - plus the scalar velocity at this point for the full, five-parameter description of the orbit (the latitude and longitude of the initial crater, and the three components of velocity at the initial point).

For any given initial velocity, it is possible to draw a region on the Shute sphere, from which region a particle must come if it is to strike the earth. For low velocities, the area (see Fig. ¹⁰⁻¹~~900~~)

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centers near 0° latitude and 90° E longitude, exactly opposite the direction of the moon's orbital motion. For higher velocities, we are dealing with orbits whose apogees are beyond the moon. Hence two areas on the Shute sphere are involved, one on the front side, for direct orbits to the earth, and the other on the far side, for movement out to the apogee and return to the earth. For ejection velocities greater than 3.1 km s^{-1} the apogee ceases to exist for orbits to the earth (the orbits are hyperbolic with respect to the earth) and hence the spots on the Shute sphere are real only on the near side. The spot approaches the center of the moon's visible face for very large velocities.

In the study of Chapman (1964), it was found that the velocity vectors for orbits to the earth all point in the same direction, namely toward the lunar equator and 90° E. This fact is illustrated in Fig. 10-2, which Chapman kindly furnished.

Fig 10-2

cr.

The initial craters are distributed widely over the moon's front face, because Chapman was interested in impact phenomena; for these, he believed that the most favorable angle to the lunar surface for the formation of tektites was around 30° to 60° to the horizontal.

If tektites come from lunar volcanoes, however, their ejecta should be nearly vertical; then the crater on the lunar surface should be just about directly below the point on the Shute sphere.

It follows that the location of the source crater should be toward the center of the eastern hemisphere, and not far from the equator.

The remote-sensing data summarized in the frontispiece of Gose (1973) indicate that the area involved has not yet been overflowed; it should show a simultaneous low of Al/Si, enhancement of gamma-radioactivity, and enhancement of the alpha-particle flux. Some trends, especially in K/U (Metzger et al, 1973) and in the rare earth ratios (Taylor et al, 1972), seem to indicate that these ratios reach more favorable values as one goes eastward toward 90° E.

The absence of inclusions of typical lunar basalts in tektites suggests that the vent is surrounded by deposits of considerable depth.

Total output

The majority of the known tektite mass is in the North American strewn field; it amounts to 100 billion tons, or about 40 cubic kilometers (Glass et al, 1973). Since only about 3 percent of the material leaving the moon is likely to hit the earth, it follows that the total amount emitted from the moon during the Cenozoic is likely to have been around 1200 cubic kilometers, or 3600 billion tons. Ejection of this amount demands the escape of at least an equal quantity of hydrogen. The total mass is, however, less than 1 millionth of the mass of the moon's

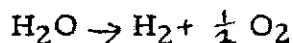
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asthenosphere (i.e. the mass below 1000 kilometers in the moon).

This figure does not give a direct measure of the volume of the source crater, because the amount of matter ejected from a volcano bears no obvious relation to the size of the vent. Note also that this larger figure assumes emission in all directions, and hence presumably includes vents which are far from the vent or group of vents responsible for the tektites.

Volcanic gases

The principal gas in terrestrial volcanism is steam. This cannot be the case for lunar volcanoes; if water is passed over a lunar magma at a temperature of 1200°C or so, it will be largely reduced to hydrogen. Consider the reaction



The ratios of the partial pressures of the gases obey the law

$$\frac{(\text{H}_2\text{O})}{(\text{H}_2)(\text{O}_2)^{1/2}} = K$$

where K is the equilibrium constant. From the JANAF tables (Stull and Prophet, 1971) at 1500°K, $\log_{10} K = 5.725$ if pressures are in atmospheres, or 3.225 if pressures are in $\text{N}\cdot\text{m}^{-2}$. The partial pressure of oxygen in equilibrium with a lunar magma at this temperature is about 10^{-13} atmospheres or $10^{-8} \text{ N}\cdot\text{m}^{-2}$;

from Walter and Doan (1969) we have for tektites, at 1500°K , the result that $\log_{10} P_{\text{O}_2}$ is -12.61 atmospheres, or $-7.61 \text{ N}\cdot\text{m}^{-2}$. From the latter figure, the ratio, $\text{H}_2\text{O}/\text{H}_2$ is 0.26 . The mean molecular weight is 5.30 ; the mean specific heat at constant pressure, C_p , is 2.85 .

This mix, of 4 parts hydrogen to one part steam, is probably the characteristic lunar volcanic gas..

The limiting velocity V_{lim} for gases at absolute temperature T escaping from an enclosure into a vacuum is

$$V_{\text{lim}} = \sqrt{2 C_p T}$$

which works out at 6.0 km s^{-1} for 1500°K and our mixture of hydrogen and steam.

By contrast, for water at this temperature, $V_{\text{lim}} = 2.4 \text{ km s}^{-1}$; this is evidently an important advantage which lunar volcanoes have for launching particles into ballistic trajectories.

It might also be possible in a lunar volcanic explosion to shock a portion of the ejecta. The explosion itself could not produce shock because the required pressures of $10^{10} \text{ N}\cdot\text{m}^{-2}$ (100 kilobars) or the like could not be contained by the lunar crust (N.M.Short, personal communication). Collisions, however, between the ejected particles, or with the walls of the

vent might well occur at velocities of several km s^{-1} , and thus might conceivably account for the coesite found by Walter (1965).

Morphology

The ballistic effects of volcanic gases on the rocks around a crater constitute a problem in hydrodynamics in which the viscosity of the fluid is unimportant. The restraining force on the material is largely gravity. For this case, the relevant non-dimensional number is the Froude number, Fr , which measures the ratio of inertial forces to gravity:

$$Fr = \frac{V^2}{gl}$$

Here V is the gas velocity, g the acceleration of gravity, and l a typical dimension (e.g. the size of the rock). For the same rock size, the lunar Froude number in a volcanic eruption will be 50 times larger than in the terrestrial case, because of the increased gas velocity and the decreased gravity. It follows that we need not expect a lunar volcano to look like a terrestrial volcano of the same size. It should be much more explosive; and the absence of an atmosphere should contribute to the violence.

Since the source volcano must be among the most recent lunar features, and since it is well known that the ray craters are also among the most recent lunar craters, it is natural to ask whether the tektite source is a ray crater.

It is usual to think of ray craters as the prototypes of

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impact craters. The original argument, however, which led to this conclusion is obsolete; it regarded the rays as light-colored rock flour thrown out of the impact crater: "powdered rock is almost always lighter than the original solid" (Baldwin, 1949, p.163). We now know that lunar fines are darker, not brighter, than the lunar rock (Shoemaker et al, 1968, p. 4028). Ray craters give strong radar reflections and strong thermal anomalies, which means that rock is exposed.

If rays are regions where exceptional amounts of rock are exposed, then we cannot comfortably say that the rock was thrown from the central crater, because, as we noted above, most of the material which is sent long distances on the lunar surface is fine material.

It is more logical to think of the rays as the paths of gaseous blasts issuing from time to time from the central crater. These would blow the accumulated dust off the tops of the rocks; in this way we can understand how the rays can appear to be the loci of small ray craters (Oberbeck, 1971). The small ray craters, with their haloes of blocks, exist everywhere, but in most places the rocks have been covered by dust; only along the rays from the great lunar craters is the dust removed. For this reason, the long-wave radar does not see the great rays (Thompson, 1970);

even in the non-ray areas it looks right through the dust, and hence sees no more blocks on the great rays than elsewhere.

Since the rate of growth of the dust layer is about $0.4 \text{ g cm}^{-2} (\text{m.y.})^{-1}$, it follows that the gaseous blasts must occur much more frequently than crater-forming events, volcanic or not, in order to maintain dust-free surfaces.

It thus does not appear unreasonable to suppose that the tektite source crater is a lunar ray crater.

Source region of the magmas

The lunar exterior differs from tektites in being more completely outgassed. The difference in the lead isotopes is particularly striking: the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio in tektites is about 18, while in the outer regions of the moon, the Apollo and Luna missions have usually found values near 200. The explanation is that ^{204}Pb is primordial; it must have been lost from the outer part of the moon in an early heating episode. On the other hand, ^{206}Pb is a decay product of ^{238}U , which is very refractory. Accordingly, tektites are not derivable from typical lunar surface rocks.

On the other hand, in the Apollo 17 orange glass, Tatsumoto et al (1973) and Silver (1974) found evidence of a lead much nearer a terrestrial lead; and in fact Silver remarks that this lead appeared to have been separated from an assemblage of U-Th-Pb

much like that believed to exist in the earth's mantle.

The tektite source region is probably at some depth.

Below 1000 km, the lunar interior is at least partly molten (Nakamura et al, 1973). Moreover, the magnesium-rich bottle-green microtektites may be xenoliths, that is, portions of the sub-crustal material of the moon carried up by the eruption.

It is even imaginable that the nickel-iron spherules of tektites, which are always found embedded in low-calcium high-aluminum tektites, are of internal rather than external origin. Conceivably they are somehow related to the core of heavy elements found by Nakamura et al (1974).

Electromagnetic behavior

The presence of magnetism in Muong Nong tektites must mean that the moon now possesses the power to magnetize rock. The most plausible explanation is lightning (Čap, 1972). This is a normal accompaniment of ash flows. It would connect the magnetism in Muong Nong tektites with the magnetism in lunar rocks, which is typically strongest in lunar breccias. The view that the lunar breccias are the product of ash flows has been brought forward by numerous authors, cited by Pai et al (1972).

The lightning furnishes a possible explanation of the orange spots sometimes seen on the moon (Middlehurst, 1966).

The spectrum of the orange spots at Aristarchus was reported by Kozyrev (1963) to be that of H_2 . The color of the H_2 spectrum agrees with that reported for the spots. The transitions which give rise to the color are between levels which are ten volts or more above ground; it follows that the required temperatures for thermal excitation would be in the tens of thousands of degrees. Only an electrical method of excitation is plausible (Mills, 1970).

THE ORIGIN OF THE MOON

The lunar origin of tektites strongly suggests that the moon must have formed by fission of the earth. Only in this way is it possible to explain the remarkable geochemical resemblance of tektites to terrestrial materials. The resemblance is so strong that at the present moment a large number of geochemists insist that tektites must be the direct products of the earth, in defiance of the physical impossibilities outlined in Chapter 9. They have repeatedly drawn attention to features of tektite composition, such as the low nickel content (Taylor, 1962a), or the high degree of differentiation (Barnes, 1958a), or the evidence of terrestrial U-Th-Pb ratios (Taylor, 1973) as evidence of the terrestrial origin of tektites, only to have the argument collapse beneath them as the same features were found on the moon. Even today, many geochemists regard

the oxygen isotope ratios, especially on 12013, as decisive proof that tektites are terrestrial rather than lunar. It is not possible to ignore these arguments; tektites are indeed much more like terrestrial rocks than would be expected for some chance assemblage.

It seems to follow that deep inside the moon there must be material very much like the mantle of the earth; in fact it must be more like the mantle of the earth than like the ultrabasic rocks which are the source regions for the lunar surface rocks. This remark was made (O'Keefe, 1972) before the finding of the earth-like lead isotopes in Apollo 17; from this finding, Silver (1974) supports the above statement about earth-like material in the moon's interior.

The very small size of the lunar core is particularly striking in this connection. It constitutes a strong constraint on hypotheses of the origin of the moon; many otherwise satisfactory ideas can be ruled out. It seems to mean either that the moon is of very primitive character, like a carbonaceous chondrite, with most of its iron oxidized, or that it is the product of fission (O'Keefe and Urey, 1975).

The fission hypothesis for the origin of the moon seems to imply a period of intense heating, from the outside, and a loss of most of the moon's original mass (O'Keefe, 1969d). This would

explain why the parts of the moon reached by most of the lunar probes show some systematic differences from tektites. The lavas constituting most of the moon's outer surface were erupted early in the moon's history, when the moon's heat was near the surface (see e.g. Toksöz et al, 1973). At present, source regions for lunar volcanism are necessarily very deep; they are therefore drawing on the material which suffered least during the period of ablation, and which therefore is most similar to unaltered terrestrial mantle materials. This may be why tektites are more like terrestrial rocks in many ways than like the rocks of the lunar surface.

POSSIBLE ECOLOGICAL IMPLICATIONS.

Urey (1973) notes that the principal strewn fields appear to be correlated with the terminations of geological periods — the North American strewn field with the end of the Eocene, the Libyan Desert glass with the end of the Oligocene, the moldavites with the end of the Miocene, and the Ivory Coast tektites, or perhaps the Australasian tektites, with the end of the Pliocene. Urey attributes the correlation to the effects, not of the tektites themselves, but of impact by very large comet heads on the earth. He considers the possibility that the dinosaurs may have been destroyed by an event of this kind.

For the reasons given in Chapter 9, we do not, in the present work, accept the idea that tektites originated by cometary impact on the earth. Let us, therefore, consider whether there may be physical reasons for the faunal changes arising directly from the tektites and microtektites themselves. We consider principally the largest of these events.

The North American strewn field (Glass, 1973) contains about 100 billion tons, of which the part studied by him is all in the range of 100 micrometers and larger. Smaller objects are difficult to sort out in the cores, both because of the limitations of the filtering methods, and because they are diluted by being spread over very large areas. The point is that the 100 micrometer particles fall out in a few hours; but 10 micrometer particles require weeks, and 1 micrometer particles, years, to fall out. Hence the 10 micrometer material is distributed all around the earth at a given latitude, and the 1-micrometer bodies will be distributed all over the earth by the wind. Hence, even though they have not yet been found, it is reasonable to suppose that there may be about as much matter in the smaller size ranges as in the observed ranges. This is what is generally observed in particle size distributions.

It can easily be calculated that a layer of rock with a

thickness of 1 micrometer has a mass of about 3 tons per square kilometer. The area of the whole earth being about 500 million square kilometers, it follows that the amount of dust, 1 micrometer in diameter, required to shut off most of the sunlight is about 1.5 billion tons; at 10 micrometers, the required amount is 15 billion tons.

It is thus possible that either large portions of the earth, or perhaps the whole earth, went through a period of weeks to a year or two with greatly diminished sunlight about 35 million years ago. The effects on the fauna and flora of that period might have been considerable.

Let us also keep in mind that if tektites are lunar, then the tektites which reach the earth are a small minority of all tektites. A much larger quantity must go into temporary geocentric orbits (Chapman, 196⁴, Shute, 1966). A cloud which trailed after the moon in its orbit would, when the line of nodes was directed toward the sun, shut off sunlight even more effectively than if it were in the earth's atmosphere. Repeated events of this kind could perhaps lower the temperature of the earth a few degrees, and so bring on a glacial period. Life on earth is at the mercy of a few micrometers thickness of dust anywhere along the earth-sun line.

It is conceivable that the onset of glaciation during the later Cenozoic is connected with the increasing frequency of eruptions from some volcanic center on the moon.

These notions should be regarded as very highly speculative; data on small microtektites are needed to test them.

SUMMARY

The available data on tektites cannot be fitted into the hypothesis that tektites are the product of terrestrial meteorite or comet impact. The discrepancies occur in at least three independent fields (cratering, glass-making and aerodynamics) and in each field amount to three or more orders of magnitude.

The only viable alternative seems to be volcanic ejection from the moon. A reasonably consistent picture of these events can be put together. They are probably rare paroxysms from a center or centers somewhere in the moon's eastern hemisphere, starting a thousand kilometers or so below the moon's surface, and involving ash flows and associated lightning.

If we have argued correctly, then the insistence of the geochemists that tektites are terrestrial must mean that the moon has

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an earth-like center, and was probably produced by fission,
followed by the ablative loss of most of the original mass.

The possibility of significant effects on the earth's climate
from clouds of microtektites in space or in the earth's atmosphere
cannot now be discounted.

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TABLE 2-1 The first scientifically significant descriptions of tektites

Australia	australites	Clarke	1855	Fig.2-7
Belitung island	billitonites	van Dijk	1879	Fig. 2-6
Malaya	indomalaysianites	Scrivenor	1909	Fig. 2-6
Tasmania	Darwin glass	Hills	1911	Fig. 2-8
Borneo		Mueller	1915	Fig. 2-6
Philippines	philippinites or rizalites	Beyer and Selga	1928 in MS 1930	Fig. 2-6
Indochina	indochinites	Lacroix	1929	Fig. 2-4
China	lei gong mo	Lacroix	1930	Fig. 2-4
Thailand	thailandites	Lacroix	1934	Fig. 2-4
Java	javanites	von Koenigswald	1935	Fig. 2-6
S.E.Asia	Muong Nong, a layered tektite with chunky external form	Lacroix	1935	Fig. 2-4
South China Sea		Saurin and Millies-Lacroix	1961	
most of the Indian Ocean	microtektites	Glass	1967	
most of the Indian Ocean	bottle-green ultrabasic microtektites	Cassidy, Glass and Heezen	1969	
S. Australian	sodium-rich tektites	Chapman and Scheiber	1969	

TABLE 2-2 Dynamical requirements for terrestrial origin
of tektite strewn fields

Strewn field	Minimum radius	Minimum velocity for terrestrial origin (km s^{-1})
Australasian	5,250	6.0
North American	1,700	4.0
Ivory Coast	600	2.4

(The velocities are taken from the tables of Hawkins and Rosenthal (1962).

TABLE 5-1 Constants of elasticity

	Moldavite	Indochinite
Longitudinal velocity	5.918 km sec ⁻¹	5.999
Shear velocity	3.627 "	3.638
Poisson's ratio	.1991	.2090
Density	2.373 g cm ⁻³	2.424
Bulk modulus	414.8 kilobar	444.4
Shear modulus	312.2 kilobar	320.9
Young's modulus	748.8 kilobar	775.9

From: Soga and Anderson, 1967

TABLE 5-2 Dispersion in tektite glass

Specimen	Wave length or color	Index of refraction	Authority
Libyan Desert glass	670.8(nm)	1.4595	Spencer and Clayton (1934)
	589.3	1.4624	"
	535.0	1.4645	"
Two moldavites	Red	1.475, 1.482	Schwantke (1909)
	Yellow (Na)	1.494, 1.490	"
	Green	1.501, 1.494	"
	Violet	1.514, 1.502	"

From: Spencer and Clayton, 1934
Schwantke, 1909.

Table 6 - 1 Central tektite composition

Element	Concentration	Authority	Element	Concentration	Authority
H	6	Fr	Ar	.00011	Re
He	4.7×10^{-12} g/g	Re	K	20,400	Ta
Li	46	Ta	Ca	21,300 14	Ta
Be	1.3	Vo	Sc		Ta
B	15	Ch	Ti	4,700	Ta
C	97	Pe	V	81	Ta
N	-	-	Cr	76	Ta
O	482,000	Ta	Mn	680	Ta
F	-	-	Fe	39,900	Ta
Ne	1.5×10^{-13} g/g	Re	Co	16	Ta
Na	11,000	Ta	Ni	35	Ta
Mg	14,400	Ta	Cu	5.6	Ta
Al	73,500	Ta	Zn	9.6	G. L.
Si	329,000	Ta	Ga	6.0	Ta
P	170	Ta	Ge	-	-
S	100	Cu	As	-	-
Cl	43	B. M.	Se	-	-

Table 6 - 1 Central tektite composition, cont.

p.2

Element	Concentration	Authority	Element	Concentration	Authority
Br	.18	B. M.	I	.22	B. M.
Kr	-	-	Xe	-	-
Rb	96	Ta	Cs	3.7	Ta
Sr	150	Ta	Ba	590	Ta
Y	25	Ta	La	60	Ta
Zr	204	Ta	Ce	84	Ta
Nb	13	Ta	Pr	11.5	Ta
Mo	.6	Ta	Nd	33	Ta
Ru	-	-	Sm	46	Ta
Rh	-	-	Eu	1.3	Ta
Pd	-	-	Gd	55	Ta
Ag	1.0?	Cu	Tb	1.0	Ta
Cd	-	-	Dy	4.3	Ta
In	< .1	Ta	Ho	12	Ta
Sn	1.0	Ta	Er	1.18	Ta
Sb	.29	Ta	Tm	0.4	Ta
Te	-	-	Yb	1.9	Ta

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Table 6 - 1 Central tektite composition

p. 3

Element	Concentration	Authority	Element	Concentration	Authority
Lu	.36	H.G.	Au	.0057	B.E.
Hf	4.0	Ta	Hg	.016	Sh
Ta	.73	Eh	Tl	0.1	Ta
W	.65	Ta	Pb	1.4	Ta
Re	.000072	L.M.	Bi	-	-
Os	.00050	L.M.	Th	13.4	Ta
Ir	.00001	Eh	U	1.9	Ta

B.M. is Becker and Manuel, 1971

H.G. is Haskin and Gehl, 1963

B.E. is Baedeker and Ehmann, 1965

L.M. is Lovering and Morgan, 1964

Ch is Chapman and Scheiber, 1969

Pe is Petersilye et al, 1968

Cu is Cuttitta et al, 1962

Re is Reynolds, 1960

(Cuttitta, 1963 for sulfur)

Sh is Showalter, 1970

Eh is Ehmann, 1963

Ta is S.R. Taylor, 1966

Fr is Friedman, 1958

Vo is Vorob'yev, 1964

G.L. is Greenland and Lovering, 1963

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TABLE 6-2a TEKTITE FAMILIES: MAJOR ELEMENTS, WEIGHT %

	1 Normal Aus	2 Normal Ind	3 Dar Gl	4 Dar Gl	5 LCaHA1	6 HMg
SiO ₂	70.4	73.3	87.7	83.2	68.1	64.76
Al ₂ O ₃	14.3	13.1	7.42	8.22	16.5	13.04
Fe ₂ O ₃			1.38*	3.20*		
FeO	4.97	4.49	-	-	5.75	8.63
MgO	2.20	2.00	0.68	2.82	2.96	7.95
CaO	2.94	2.17	0.02	0.16	1.82	2.85
Na ₂ O	1.56	1.27	0.01	0.19	1.08	0.72
K ₂ O	2.49	2.36	1.62	1.72	2.52	1.34
TiO ₂	0.82	0.89	0.52	0.52	0.92	0.71
P ₂ O ₅						
Mn						

Physical Properties

S.G.	2.450	2.428			2.481	2.591
R.I.	1.513	1.508			1.519	1.544

* All Fe as Fe₂O₃

1. Normal australite, Chapman and Scheiber, 1969b, No. 45.
2. Normal indochinite, Chapman and Scheiber, 1969b, No. 52
3. Darwin-Macedon glass, Chapman et al, 1967a, No. DG - 5.
4. Darwin-Macedon glass, Chapman et al, 1967a, No. Macedon 3531.
5. Low calcium, high aluminum tektite, Chapman and Scheiber, 1969b, No. 42.
6. High magnesium tektite, Chapman and Scheiber, 1969b, No. 11.

TABLE 6-2b TEKTITE FAMILIES: MAJOR ELEMENTS, WEIGHT %

	7 BottleGr	8 Normal Aus	9 H Na/K	10 Normal Phil	11 HCa
SiO ₂	51.6	59.2	63.4	71.6	68.6
Al ₂ O ₃	14.7	22.1	16.8	13.0	11.0
Fe ₂ O ₃					
FeO	4.44	3.5	5.67	4.55	4.55
MgO	21.4	5.8	3.69	2.42	2.43
CaO	4.16	4.5	4.49	3.31	9.77
Na ₂ O	0.06	0.7	3.84	1.50	0.93
K ₂ O	0.06	0.3	1.08	2.47	1.77
TiO ₂	0.73	n.d.	.58	0.78	0.62
P ₂ O ₅					
MnO		0.1			

Physical Properties

S.G.	2.786 ±.015		2.535+	2.451	2.535
R.I.		1.509	1.532	1.513	1.534

7. Bottle-green Australasian microtektite, Glass, 1972b, No. 84-1.
8. Normal Australasian microtektite, Cassidy et al, 1969, No. 43.
9. High sodium/potassium, Chapman and Scheiber, 1969b, No. 24.
10. Normal philippinite, Chapman and Scheiber, 1969b, No. 48.
11. High calcium philippinite, Chapman and Scheiber, 1969b, No.6.

TABLE 6-2c TEKTITE FAMILIES: MAJOR ELEMENTS, WEIGHT%

	12 Moldavite	13 Moldavite	14 Moldavite	15 Georgia	16 Bediasite	17 Bediasite
SiO ₂	84.48	79.10	75.5	83.6	76.2	71.89
Al ₂ O ₃	7.79	9.75	11.12	9.50	13.4	17.56
Fe ₂ O ₃	0.21	0.07	0.29	0.01	0.27	0.27
FeO	0.98	1.52	1.50	1.82	3.74	5.26
MgO	1.72	1.98	2.20	0.42	0.74	0.78
CaO	1.90	2.89	3.40	0.40	0.74	0.45
Na ₂ O	0.20	0.69	0.48	1.19	1.63	1.28
K ₂ O	2.40	3.47	3.68	2.51	2.22	1.60
TiO ₂	0.22	0.57	0.31	0.42	0.74	1.05
P ₂ O ₅	0.03			0.03	0.05	0.04
MnO	0.05					

Physical Properties

S.G.	2.331	2.366	2.303	2.384	2.416
R.I.	1.491	1.492	-	1.4962	1.5076

12. High silica moldavite, Schnetzler and Pinson, 1964a, No. T 4574.

13. Central moldavite, Bouska and Povondra, 1964, No. 3.

14. Low silica moldavite, Philpotts and Pinson, 1966, No. T 5296f.

15. Georgia tektite, Cuttitta et al, 1967, No. Ga.2345.

16. Medium silica bediasite, Cuttitta et al, 1967, No. B-6.

17. Low silica bediasite, Cuttitta et al, 1967, No. B-90.

TABLE 6-2d TEKTITE FAMILIES: MAJOR ELEMENTS, WEIGHT %

	18 Micro NA	19 Micro NA	20 IvorCo	21 IvorCoBotGr	22 Aouelloul	23 LibDesGl
SiO ₂	64.4	58.20	67.6	51.4	84.65	98.20
Al ₂ O ₃	16.7	5.35	16.8	16.0	6.0	0.70
Fe ₂ O ₃		-			0.62	0.53
FeO	6.79	8.57	6.14	10.5	1.96	0.24
MgO	2.87	12.60	3.12	20.0	1.08	0.01
CaO	2.49	11.40	1.49	2.75	0.30	0.30
Na ₂ O	1.48	0.50	2.04	0.40	0.24	0.33
K ₂ O	3.70	0.92	1.87	0.12	1.97	0.02
TiO ₂	0.90		0.52	0.50	0.65	0.23
P ₂ O ₅					0.04	
MnO	0.09	0.34			0.047	

Physical Properties

S.G.

2.484

R.I.

1.519

1.5956

18. North American microtektite, Glass, 1973, No. 19.

19. North American crystalline spherule, like North American bottle-green,
C. John and B.P. Glass, to be published in Geology.

20. Ivory Cost tektite, Chapman and Scheiber, 1969b, No. 62.

21. Ivory Cost bottle-green microtektite, Glass, 1972b, No. 120.

22. Aouelloul crater glass, C.S. Ansell, unpublished.

23. Libyan Desert glass, Spencer, 1939, average.

TABLE 6-3a TEKTITE FAMILIES: TRACE ELEMENTS, ppm

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	1 Normal Aus	2 Normal Ind	3 Dar Gl	4 Dar Gl	5 LCaHA1	6 HMg
Ag						
B	15	12			27	11
Ba	410	365	300	400	390	410
Be			2.6	2.6		
Co	13	11	4	34	13	56
Cr	78	80	46	160	125	440
Cs			3.1			
Cu	5	~ 4	1.4		n.d.	5
Dy						
Eu						
Ga			< 5	8.7		
Ge						
La						
Li						
Mn	820	730	50	245	910	1700
Nb			18	19		
Ni	28	16	71	500	30	230
Pb						
Rb			105	90		
Sc			7.8	8.5		
Sr			17	16		
Th						
U						
V	83	76	16	20	105	80
Y	32	31	58	50	34	32
Zn						
Zr	350	320	600	395	245	230

TABLE 6-3b. TEKTITE FAMILIES: TRACE ELEMENTS, ppm

	7 Bottle Gr	8 NormalAus	9 HN a /K	10 NormalPhil	11 HCa
Ag					
B			11	39	22
Ba			355	400	380
Be					
Co			46	13	18
Cr	1500		235	105	105
Cs					
Cu			16	8	n.d.
Dy					
Eu					
Ga					
Ge					
La					
Li					
Mn	800		770	670	1700
Nb					
Ni			675	35	43
Pb					
Rb					
Sc					
Sr					
Th					
U					
V			97	87	90
Y			< 15	32	35
Zn					
Zr			165	270	250

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TABLE 6-3c TEKTITE FAMILIES: TRACE ELEMENTS, ppm

12-13-14 Moldavite: trace elements from various sources.		15 Georgia	16 Bediasite	17 Bediasite
Ag		<1	<1	2
B	9	<10 ?	<10	30
Ba		715	440	420
Be	2	Preuss 1.9	2	5
Co	-	6.7	11	12
Cr	40	Preuss 18	46	62
Cs		1.4	1.7	2.3
Cu	5.4	Greenland & Lovering 3.2	10	14
Dy	2.8	Chase et al		
Eu	.83	Chase et al		
Ga	-	- 9.0	11	16
Ge	-	-		
La	29	Chase et al <50	50	40
Li	14	Goldschmidt et al 14	22	24
Mn		218	200	170
Nb		<10	18	22
Ni	15	Preuss 1935 9.5	16	14
Pb	6	Tilton		
Rb	135	80	72	54
Sc	3	Goldschmidt & Peters 1932 7.8	10	16
Sr	136	Pinson et al 1956 153	85	60
Th	15.4	Dubey		
U	2.2	Starik et al Adams et al Dubey		
V		37	120	100
Y	2	Goldschmidt & Peters 20	20	30
Zn	7.6	Greenland & Lovering		
Zr	140	von Hevesy & Wurslin 1916 120	220	260

TABLE 6-3d TEKTITE FAMILIES: TRACE ELEMENTS, ppm

	18 Micro NA	19 Micro NA	20 IvorCo	21 IvorCoBotGr	22 Aouelloul	23 LibDesGl
Ag		600				
B			20		2	
Ba			650		420	
Be					-	
Co			19		20	
Cr			210		70	
Cs					1.4	
Cu			12		9.5	
Dy					-	
Eu					-	
Ga					8	
Ge					-	
La					-	
Li					12	
Mn			555	1100	340	
Nb					10	
Ni			86		360	200
Pb						
Rb					66	
Sc					12	
Sr					44	
Th						
U						
V			95		2	
Y			16		14	
Zn					58	
Zr			140		810	

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Table 6-4
Comparison, Ries glasses and moldavites

	Type I glasses(9)	Type II glasses(6)	Type III glasses(17)	Type III Mixture of glasses(8)	Moldavites (29)
SiO ₂	63.54	62.07	64.04	65.32	79.06
TiO ₂	0.81	0.85	0.78	0.66	0.47
Al ₂ O ₃	15.10	14.72	15.28	14.88	10.50
Fe ₂ O ₃	0.99	1.25	1.42	1.59	0.30
FeO	3.75	3.37	2.39	2.39	1.75
MnO	0.10	0.13	0.08	n.d.	0.09
MgO	2.71	2.63	1.71	1.83	1.79
CaO sil.	3.00	2.98	3.58	3.10	2.19
CaO carb.	0.45	0.64	0.40	0.66	—
Na ₂ O	2.86	3.53	3.59	3.08	0.58
K ₂ O	3.71	3.29	3.50	3.13	3.33
P ₂ O ₅	0.36	0.36	0.32	0.50	0.02
H ₂ O+	2.73	3.58	2.72	2.18	—
CO ₂	0.37	0.53	0.33	0.44	—

From Von Engelhardt, 1967.

Types I, II, and III are Ries glasses of increasing degrees of recrystallization.

Table 6-5

Major element composition of Ivory Coast tektites and selected glasses from Bosumtwi crater.

	Green BCC-8a-2-64	Black BCC-8a-3-64	White BCC-8b-2-64	Grey BCC-5a-2-64	Ivory Coast Average (7)
SiO ₂	65.30	65.2 ₆	98.2	65.8	68.0 ₂
Al ₂ O ₃	17.4 ₄	16.5 ₂	0.43	17.1	16.3 ₀
Fe ₂ O ₃	1.03	1.94	0.31	3.32	0.57
FeO	4.94	4.54	0.11	1.98	5.99
MgO	2.61	2.66	0.00	0.80	3.32
CaO	2.53	2.57	0.00	1.58	1.12
Na ₂ O	2.90	2.59	0.11	3.64	2.06
K ₂ O	1.88	1.87	0.00	1.38	1.89
H ₂ O [±]	0.40	1.49	0.65	3.67	—
TiO ₂	0.61	0.67	0.01	0.73	0.57
P ₂ O ₅	0.14	0.10	0.00	0.08	0.04 ₈
MnO	0.10	0.07	0.01	0.04	0.06 ₈
TOTAL	99.88	100.2 ₈	99.83	100.1 ₂	100.03
Total Fe as Fe ₂ O ₃	6.52	6.98	0.43	5.42	7.23

From Cuttitta et al, 1972.

For minor and trace element comparison, see Fig. 6-8.

TABLE 9- Comparison, lunar sialic particles and tektites

Oxide	1 Apollo 11 (Cf col 6)	2 Apollo 12 (Cf col 7)	3 Apollo 14 (Cf col 8)	4 Apollo 15 (Cf col 9)	5 Luna 16 (Cf col 1)	6 Moldavite	7 HCa philippinite	8 N.Am.micro- tektite	9 Australasian microtektite
SiO ₂	75.6	57.1	73.9	62.54	77.6	80.3	68.6	74.1	64.6
TiO ₂	0.5	0.39	0.64	1.18	n.d.	0.60	0.62	0.70	0.7
Al ₂ O ₃	12.0	15.8	12.5	15.73	11.3	9.62	11.0	15.6	17.6
All Fe as FeO	2.2	7.4	3.2	6.67	1.4	1.66	4.55	3.86	5.4
MnO	-	0.09	.06		-	0.07	.22	0.06	0.1
MgO	0.3	5.4	1.1	2.51	n.d.	1.10	2.4	1.41	3.5
CaO	1.9	10.3	2.0	6.86	1.0	1.88	9.77	1.13	4.2
Na ₂ O	0.4	1.84	1.3	0.98	0.5	0.37	0.93	0.90	1.0
K ₂ O	6.1	1.27	4.9	3.20	6.3	3.65	1.77	2.90	1.8

Col. 1 Reid et al, 1972a (lunar) Table 1

Col. 2 Glass, 1971b (lunar); analysis #26

Col. 3 Glass et al, 1972a (lunar), high silica fragment

Col. 4 Reid et al, 1972b, "Granite" 2

Col. 5 Reid et al, 1972a (lunar) Table 5

Col. 6 Rost, 1972, p.111, no.4

Col. 7 Chapman and Scheiber, 1969, Analysis No. 6

Col. 8 Glass et al, 1973, #2

Col. 9 Cassidy et al, 1969, Analysis # 59

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TABLE 6-7 Libyan Desert glass vs lunar cristobalite

	Libyan Desert glass			Lunar cristobalite (& analyses)	Lunar tridymite (10 analyses)
	1934	1939 I	1939 II		
SiO ₂	97.58	97.97	98.44	97.9	96.6
TiO ₂	0.21	0.21	0.25	0.34	0.41
Al ₂ O ₃	1.54	0.91	0.49	0.97	1.08
Fe ₂ O ₃	0.11	0.54	0.53		
FeO	0.23	0.24	—	0.25	0.40
NiO	tr	0.032	0.016		
MnO	tr	—	—		
MgO	tr	0.01	0.01	0.01	0.08
CaO	0.38	0.05?	0.30	0.21	0.49
Na ₂ O	0.34	0.33	—	0.17	0.10
K ₂ O	nil	0.02	—	0.01	0.09
H ₂ O ⁺	0.05	0.03	—		
H ₂ O ⁻	0.05	0.03	—		

Libyan Desert glass 1934 is from Clayton and Spencer (1934). L.D.G. 1939 is from Spencer (1939). The analyses of lunar cristobalite are from: Brown et al (1970) (2); Dence et al (1970) (1); Kushiro and Nakamura (1970) (1); Lovering and Ware (1970) (1); Klein, Drake and Frondel (1971) (1); Weill et al (1971) (1). The 10 analyses of lunar tridymite are from: Brown et al (1970) (1); Dence et al (1970) (1); Keit et al (1970) (1); Klein, Drake and Frondel (1971) (1); Weill et al (1971) (2).

Table 6-8 Mesosiderite vs bottle-green microtektites

	Estherville	Bottle-green
SiO ₂	55.4	56.3
Al ₂ O ₃	8.4	10.8
Feo	11.8	7.7
MgO	14.2	18.2
CaO	5.6	4.0
Na ₂ O	-	0.8
K ₂ O	< 0.01	0.4
TiO ₂	0.4	0.6
MnO	0.5	0.1

Col.1, from Powell, 1971.

Col.2, Average of 7 bottle-green microtektites in Cassidy et al, 1969.

Table 6 - 9 Aouelloul glass vs Zli sandstone

	Zli sandstone Fudali's expeditions			Aouelloul Fudali		Aouelloul glass Chao's 1964 specimens		
	Min	Avg	Max			Min	Avg	Max
Cu	3.1	4.9	8.4	6.2,	7.4	6.4	11.4	16
Ga	2.8	3.9	6.2	6.0,	5.8	8	9	10
Li	2.5	5.0	13	12,	10	12	13	15
Rb	27	57	92	94,	86	63	68	73
Mn	21	129	408	365,	370	330	360	455
Cr	13	23	31	69,	60	62	67	70
Co	<2	-	2.8	19,	18	16	20	22
Ni	<1	7.3	14	215,	215	335	360	415
Ba	100	426	1100	340,	280	425	455	520
Sr	12	32	62	46,	46	39	42	46
V	7.4	14	18	23,	20	22	26	31
B	52	74	150	31,	140	10	12	18
Nb	<10	-	13	40,	11	13	14	17
Sc	<2	<2.2	2.9	4.4,	4.4	12	13	14
Y	4.8	17	79	20,	20	14	16	16
Zr	410	631	830	750,	640	760	800	840

Analyst: C.S. Annell

Cols. 1 - 3, 10 specimens from R. Fudali, 9 of them chosen to give a good sampling of the whole Zli.

In Col. 4, the second entry is dust removed from the specimen in the cleaning process..

Cols. 5 - 7 are measurements on 4 glass specimens partially reported in Chao et al, 1966b.

TABLE 7-1 K-Ar and fission-track ages of tektite strewn fields, in millions of years

Materials	K-Ar	Authority	Fission track	Thermal correction?	Authority
<u>Australasian</u>					
Australites	0.72 \pm 0.06	Zähringer 1963b 6 specimens	0.7 \pm 0.1	Yes	Gentner, Storzer, and Wagner 1969
Indochinites	0.73 \pm 0.06	" 3 "			
Philippinites	0.70 \pm 0.07	" 5 "			
Thailandites, billitonites, javanites, Borneo tektites	0.72 \pm 0.06	" 4 "			
Darwin glass			0.72 \pm 0.1	Yes	"
Muong Nong			0.7 \pm 0.1	Yes	"
Microtektites			0.71 \pm 0.1	Yes	Gentner, Glass, Storzer, and Wagner 1970
<u>Ivory Coast</u>					
Land tektites	1.1 \pm 0.1	Gentner, Kleinman and Wagner 1967	1.02 \pm 0.1		Gentner, Kleinman, and Wagner 1967
Microtektites			1.09 \pm 0.20		
Bosumtwi glasses	1.3 \pm 0.3	Gentner et al 1964			
Ata glass			1.04 \pm 0.2		"

Table 7 - 1 Cont.

Materials	K-Ar	Authority	Fission track	Thermal Authority correction?
<u>Moldavites</u>	14.7 \pm 0.7	Gentner, Kleinman and Wagner 1967	14.1 \pm 0.6	Gentner, Storzer and Wagner 1967
<u>Ries glasses</u>	14.7 \pm 0.6	Gentner et al 1963 (mean with G, K, W 1967)	14.0 \pm 0.6	"
<u>Libyan Desert Glass</u>			26.6 \pm 6.3 -1.3	Yes Gentner, Storzer and Wagner 1969
			28.5 \pm 2.3	Yes Storzer and Wagner 1971
<u>North American tektites</u>				
Cuban			35	Garlick, Naeser, and O'Neil 1971
Bediasites	} 34.2		34.2 \pm 2.0	Yes Storzer and Wagner 1971
Martha's Vineyard		Zähringer 1963b 9 specimens	36.4 \pm 1.5	Yes "
Georgia			1.0 \pm 0.1 6.3 \pm 0.7	Yes "
Microtektites			34.6 \pm 4.2	Yes Glass et al

Table 7 - 1, cont

p. 3

Materials	K-Ar	Authority	Fission track	Thermal Authority correction? correction
<u>Aouelloul</u>	18.6	Gentner, Kleinman, Storzer and Wagner 1960	0.46 \pm 0.10	Fleischer, Price and Walker 1965
			0.38 \pm 0.08	
			0.16 \pm 0.06	
			0.16 \pm 0.05*	"
			0.49 \pm 0.09*	
			0.50 \pm 0.16	
			0.57 \pm 0.1*	Wagner 1966
			0.59 \pm 0.1*	
			0.61 \pm 0.1	
			3.3 \pm 0.5	Yes Storzer 1971

* Falsely attributed to Bosumtwi

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TABLE 7-2 Lead, Uranium and Thorium isotopic history

Isotope	Decay constant (yr^{-1})	Initial abundance relative to ^{204}Pb	Modern abundance relative to ^{204}Pb
^{204}Pb	0	1.00	1.00
^{206}Pb	0	9.5	18.9
^{207}Pb	0	10.3	15.8
^{208}Pb	0	29	38
^{232}Th	-4.99×10^{-11}	44	35
^{235}U	-9.72×10^{-10}	5.6	.067
^{238}U	-1.54×10^{-10}	18.6	9.2

TABLE 7-3 Isotopes of lead, uranium, and thorium in tektites

Source	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{232}\text{Th}/^{204}\text{Pb}$	$^{235}\text{U}/^{204}\text{Pb}$	$^{238}\text{U}/^{204}\text{Pb}$
Australite	18.81	15.60	38.7	210	0.28	38.7
Moldavite	18.55	15.65	38.4	-	-	-
Philippinite	18.83	15.70	39.1	-	-	-
Libyan Desert Glass	19.11	15.75	39.2	-	-	-

(Recalculated from Tilton, 1958).

TABLE 9-1 Ratio of silicon monoxide to silicon dioxide
as a function of temperature

Temperature ($^{\circ}\text{K}$)	$\log K$	$\log_{10} \text{SiO/SiO}_2$
1000	-6.3	-6.0
1400	-3.3	-3.0
1800	-1.7	-1.3
2200	-0.6	-0.3
2600	-0.1	+0.3
3000	+0.6	+1.0

Legends for Text Figures

1-1 Artefacts made from Libyan Desert glass. Of Aterian age.

From Oakley, 1952. (Nature, Vol. 170, p. 448. ©1952 by Macmillan and Co. Ltd.)

1-2 Drawing of an australite by Charles Darwin (1844). The specimen is 28 mm in length.

2-1 Tektite strewn fields. Ocean floor cores, with microtektites, @.

2-2 The distribution of known meteorite falls and finds. It reflects human activity in meteoritics; it contrasts with 2-1. After V. F. Buchwald (1968).

2-3 The Australasian strewn field, exhibiting the minimum velocity required to reach the edges of the field from the most favorably located site. O'Keefe, 1969c. (J. Geophys. Res. 74, 6796. ©1969, American Geophysical Union.)

2-4 The distribution of the australites. After Baker, 1959b. (Mem. Nat. Mus. Vict. No. 23, p. 18).

2-5 The distribution of billitonites, jawinites and related tektites. From Barnes, 1963b. (Tektites, p. 31. ©1963 by the University of Chicago.)

2-6 Distribution of indochinites and thailandites. From Barnes, 1963b. (Tektites, p. 34. ©1963 by the University of Chicago.)

2-7 Distribution of philippinites. After Barnes, 1963b. (Tektites, p. 37. ©1963 by the University of Chicago).

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2-8 Chemical and physical matches between widely separated points in the Australasian strewn field. D. R. Chapman, 1971. (J. Geophys. Res., Vol. 76, p. 6317. © 1971 by American Geophysical Union.)

2-9 The Macedon-Darwin glass strewn field.

2-10 The Ivory Coast strewn field. Tektite locations: ⊕ = on land; ⊙ = in ocean cores (microtektites); ● = cities; ○ = Bosumtwi crater.

2-11 The moldavite strewn field: ● = tektite locations; ○ = cities.

2-12 The bediasites, superimposed on a geologic map of Texas. Barnes, 1963b. (Tektites, p. 40. © 1963 by the University of Chicago.)

2-13 The Libyan Desert glass strewn field. Mind Nat.

3-1 The formation of flanged australites. After Baker, 1956b.

A-H. Successive stages in the ablation of a glass sphere (A) entering the earth's atmosphere. Note that the flanges do not appear until stage E, when over half the mass is lost; and they break off for the last stages (G, H). (Mem. Nat. Mus. Vict. No. 20, p. 91.)

3-2 Depth of ablation in australites. O'Keefe et al, 1973 (full lines) agree closely with Chapman and Larson, 1963b (marginal ticks). (J. Geophys. Res. vol. 78, p. 3494. © 1973, American Geophysical Union.)

4-1 Homogeneity of tektites, determined by microprobe scans. From an unpublished paper of L. S. Walter by kind permission. Ga = Georgia tektite; Aust = australite; indo = indochinite; phil = philippinite; mold = moldavite; I.C. = Ivory Coast tektite. Note that only the Muong Nong tektite is inhomogeneous.

4-2 Homogeneity of tektites. From Walter, unpublished. See under 4-1.

4-3 Inhomogeneity in a Muong Nong tektite. Metal oxides content inversely correlated with silica content. This means that the inhomogeneity in the Muong Nong is the result of mixing glasses of differing composition, not minerals. L. S. Walter, unpublished. See under 4-1.

5-1 Specific gravity vs silica content.

5-2 Refractive index vs silica content.

5-3 Spectral transmittance in the optical and near infra-red. From Stair, 1955. (Geochimica et Cosmochimica Acta, Vol. 7, p. 46. ©1955, Pergamon Press.)

5-4 Spectral transmittance of tektite glass in the far infra-red.

Note that the scale is opened up by a factor of about 10 between the dotted curve and the solid curve. There is a similar break between Fig. 5-3 and 5-4; tektite glass becomes very opaque at longer wavelengths. Perry and Wrigley, 1967; Kadushin and Vorob'yev, 1962.

5-5 Reflectivity curves: _____ moldavite; - - - - indochinite; and - . - . - philippinite. From Perry and Wrigley, 1967. (Applied Optics, Vol. 6, p. 586. ©1967 by the Optical Society of America.)
Note the reststrahlen at 457 and 1060 cm^{-1} (21.9 and $9.4\text{ }\mu\text{m}$).

5-6 Optical constants of a moldavite. Real part of index of refraction n _____; imaginary part - - - - . The index of refraction goes from the optical values shortward of the reststrahlen to the radio-frequency values on the long-wavelength side of the reststrahlen. (Applied Optics, Vol. 6, p. 586. ©1967 by the Optical Society of America).

- 5-7 Viscosity as a function of inverse Kelvin temperature. See text for references.
- 5-8 Effective binary diffusion coefficients of iron and silicon in tektite glass as a function of inverse Kelvin temperature. From Varshneya, 1970. (Dissertation, p. 140. Case-Western Reserve University).
- 6-1 Comparison of central tektite composition (Table 6-1) with USGS standard granite G-1. Bar is proportionate to logarithmic excess, positive upward. "Volatile elements" means elements having volatile compounds, especially oxides. G-1 from Flanagan, 1973.
- 6-2 As for 6-1, comparing central tektite with W-1, USGS standard basalt, Flanagan, 1973.
- 6-3 As for 6-1, comparing central tektite composition with AGV-1, USGS standard andesite, Flanagan, 1973.
- 6-4 As for 6-1, comparing central tektite composition with Henbury subgraywacke (S.R. Taylor, 1966).
- 6-5 As for 6-1, comparing basaltic clast 14321.223 (Apollo 14, Wänke et al, 1972) with W-1.
- 6-6 As for 6-1, comparing central tektite composition with lunar sample 12013 (various authors).
- 6-7 Sketch showing the chemical relations of the tektite clans which constitute the Australasian strewn field. The numbers 1-11 refer to the corresponding columns of Tables 6-2a and 6-2b.

- 6-8 Sketch showing the chemical relations of the tektite clans not in the Australasian strewn field. The numbers 12-23 refer to the corresponding columns of Tables 6-2c and 6-2d.
- 6-9 As for 6-1, comparison of central tektite composition with Bosumtwi green and black glass (Cuttitta et al, 1972).
- 6-10 Chemical trends for MgO and K_2O in bottle-green microtektites (+, @, O) with those in 12013 (●), KREEP (■) and some lunar ultrabasics (▲).
- 6-11 See legend for 6-9. CaO and Al_2O_3 .
- 6-12 See legend for 6-9. FeO and Na_2O .
- 7-1 Rubidium-strontium isotope plot for Ivory Coast tektites (and other tektites). From Schnetzler et al, 1966. (Science, Vol. 151, p. 818. ©1966 by the American Association for the Advancement of Science).
- 8-1 Two ways by which radiation pressure can exert a torque on a body in space.
- 9-1 Mineral grains and microtektites in a core sample, from the Australasian strewn field. Courtesy of B. P. Glass. (J. Geophys. Res., Vol. 74, p. 6797. ©1969 by the American Geophysical Union).
- 10-1 The Shute sphere. Map of moon's eastern hemisphere, showing the regions from which a body, leaving the moon's surface vertically at the stated velocity, would reach the earth. Redrawn from Shute, 1966. (Astronomical Journal, Vol. 71, p. 606. ©1966 by the American Institute of Physics).

10-2 Chapman's chart showing initial direction required for rays from various lunar craters to reach the earth. These are nearly parallel to the vertical directions indicated on the Shute sphere. (unpublished; courtesy of D. R. Chapman.).

~~P. 1~~ 394

PLATE LEGENDS

[N.B.: i is for image. The i-numbers are preliminary; the images will be assembled into plates at some stage, and will be given plate numbers.]

i-1 Venus of Willendorf. Statuette, cm in height, found at Willendorf in Austria, associated with three small knives (now lost) made of moldavite glass. Praehistorische Abteilung, Naturhistorisches Museum, Vienna.

i-2, i-3 Australite, partially flaked for use as a tool. The flaked surfaces are not corroded. Loaned by Brian Mason.

i-4, 4-5 Billitonites. The projections appear to be remnants of the outer shell, which have elsewhere spalled off. Courtesy of G.H.R. von Koenigswald.

i-6, i-7 Indochinites from Viet Nam, Smithsonian USNM 2141. The surfaces which were originally in bubbles are uncorroded; hence the corrosion process must have stopped before the bubbles were broken. 3g, 2g.

i-8 Microtektites. North American strewn field. Courtesy of B.P.Glass.

i-9, i-10 Muong Nong tektite glass from Muong Nong, Laos. Note the layering and the rough, gritty exterior. NMNH 5424. 344g. Smithsonian collection.

i-11, i-12, i-13 Splash-form tektites. From a Thai lapidary. NMNH 2581. Smithsonian collection.

i-14 Cast of Ivory Coast tektite, showing cupules. Smithsonian collection.

i-15 Bediasites. B78 (right) and B58 (left). Smithsonian. Note the gouges.

i-16, i-17 Billitonite. USNM 3163. Smithsonian. Note the meandrine grooves, on only one side (probably the anterior side).

i-18 Anda tektite. Cast of specimen belonging to E.C.T. Chao. Note the system of multiple grooves.

i-19 Flanged australites. Courtesy of British Museum.

i-20 Striae in australite slice. The striae meet the posterior surface at a steep angle; but on the anterior surface they turn, and follow the surface, as a result of liquid flow. Courtesy of D.R. Chapman.

i-21 Three australites, diameters 16 to 26 mm, and three artificial models ablated in the NASA-Ames arc jet. Courtesy D.R.Chapman.

i-22 Flange formation on a javanite. Courtesy G.H.R.von Koenigswald. Note the thickness of the melt layer, compared to the australite (i-20).

i-23 Comparative morphology of flangeless australites, billitonites, ~~javanites~~ and philippinites. The meandrine grooves appear on the anterior (lower) side, which has apparently suffered spallation. Note the sharp keel, separating anterior and posterior faces. Courtesy D.R.Chapman.

i-24 Thailandite , NMNH 2349. Interior surface, showing little corrosion.

i-25 Same as i-24; exterior corroded surface. Note bald spot on lower edge.

i-26 Same as i-24 and i-25; edge view showing bald spot.

i-27 Lei-gong-mo (Chinese tektite) from the island of Tung Hai (Tan Hai). View showing former bubble walls. Note lack of corrosion on walls and on broken edge. Smithsonian.

i-28 Exterior view of same tektite as i-27; note corrosion.

i-29 Casts of two tektites showing plastic breaks. Courtesy of H.H.Nininger and G.Huss. Note that the corrosion must have occurred while the tektite was still hot and plastic, since the surfaces exposed by the plastic break are uncorroded.

i-30 Bald spot on one of the tektites of i-29. Possibly the result of aerodynamic ablation on a rough surface.

i-31 Moldavite with radial gouges. NMNH 3172, Smithsonian.

i-32 Reverse of i-31.

i-33 Indochinite, Viet Nam. NMNH2141, Smithsonian.

i-34 Reverse of i-33, showing bald spot and streaky structure.

i-35 Philippinite, Coco Grove (Bikol type). NMNH 2039-3, Smithsonian. Note deep meandrine grooves.

i-36 As for i-35. NMNH 2039-11, Smithsonian.

i-37 Lei-gong-mo from Kwang-Chow Wan, No. 4. Smithsonian. Note bald spot.

i-38 Libyan Desert glass. NMNH 5739, Smithsonian. Note wind-faceted surface.

i-39 Reverse of i-38 Surface partly wind-facettted and partly corroded.

i-40 Darwin glass. NMNH 5642, Smithsonian.

i-41 Aouelloul glass. NMNH 5617. Note layered structure.

i-42 Moldavite, about 3 cm diameter, from Smithsonian collection. Immersed in light machine oil, and viewed between crossed polaroids to show internal strain polarization due to rapid cooling as a unit.

i-43 Spinous voids in Muong Nong tektite from Phaeng Dang.

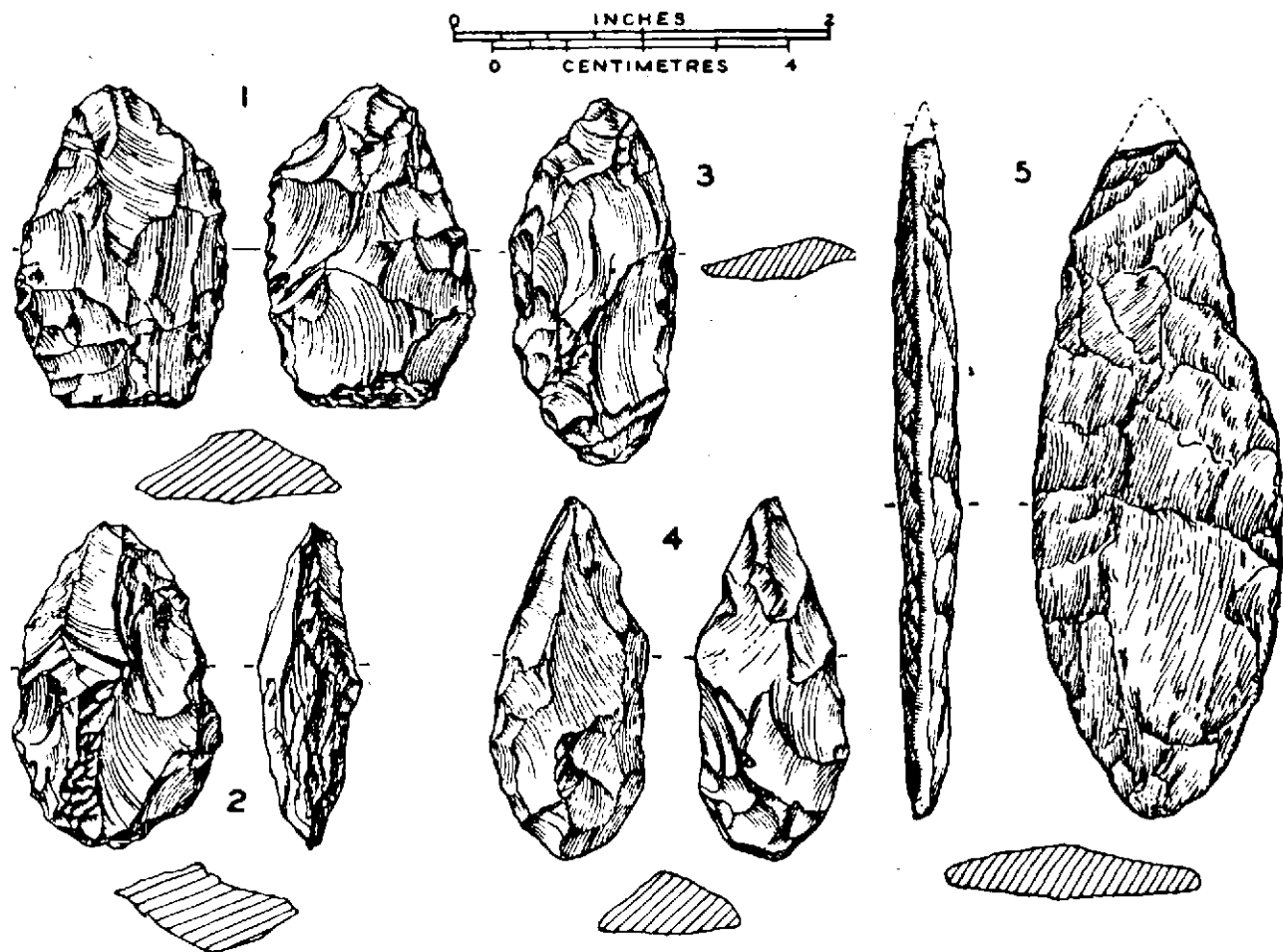
i-44 Fine structure in a Muong Nong tektite revealed by etching with HF . Photo by L.S.Walter.

i-45 Lechatelierite, in a moldavite from Lhenice, USNM 2057-2, courtesy of E.C.T.Chao and the University of Chicago Press.

i-46 Quartz grains, in thin section between crossed polaroids. In Muong Nong tektite from Nong Sapong, loaned by V.Barnes.

i-47 Impact glass from Ries crater, showing inhomogeneity.

i-48 Lunar volcanic craters in Alphonsus.



Drawn by C. O. Waterhouse.

PROBABLE ATERIAN ARTEFACTS FROM LIBYAN SAND SEA

- (1) Miniature foliate 'hand-axe' in silica-glass ; plano-convex ; probably made from thick flake. The straight basal margin is a natural surface pitted by sand-blast. The *arrêtes* of the flake-scars are slightly smoothed. Brit. Mus. (Nat. Hist.) Geol. Dept. *E. 1454*
- (2) Miniature foliate 'hand-axe' in silica-glass. The narrow area on one face which shows shallow pitting is a remnant of a surface which was sand-blasted before the material was worked. The flaked surfaces are slightly smoothed by sand-blast. *E. 1453*
- (3) Thin, twisted, bifaced foliate point in silica-glass. Slightly smoothed by sand-blast. Perforated by meandering tubular cavity, 0.6-1.5 mm. in diameter, which is blocked at the narrower end by a particle of loam. *E. 1455*
- (4) Bifaced foliate point in silica-glass ; plano-convex ; probably made from a flake. All the edges are smoothed by sand-blast, the convex surface considerably so. *E. 1456*
- (5) Bifaced foliate point in quartzite. Tip broken. Slightly worn by sand-blast. *E. 1452*

J.A.O'Keefe

Fig. 1-1

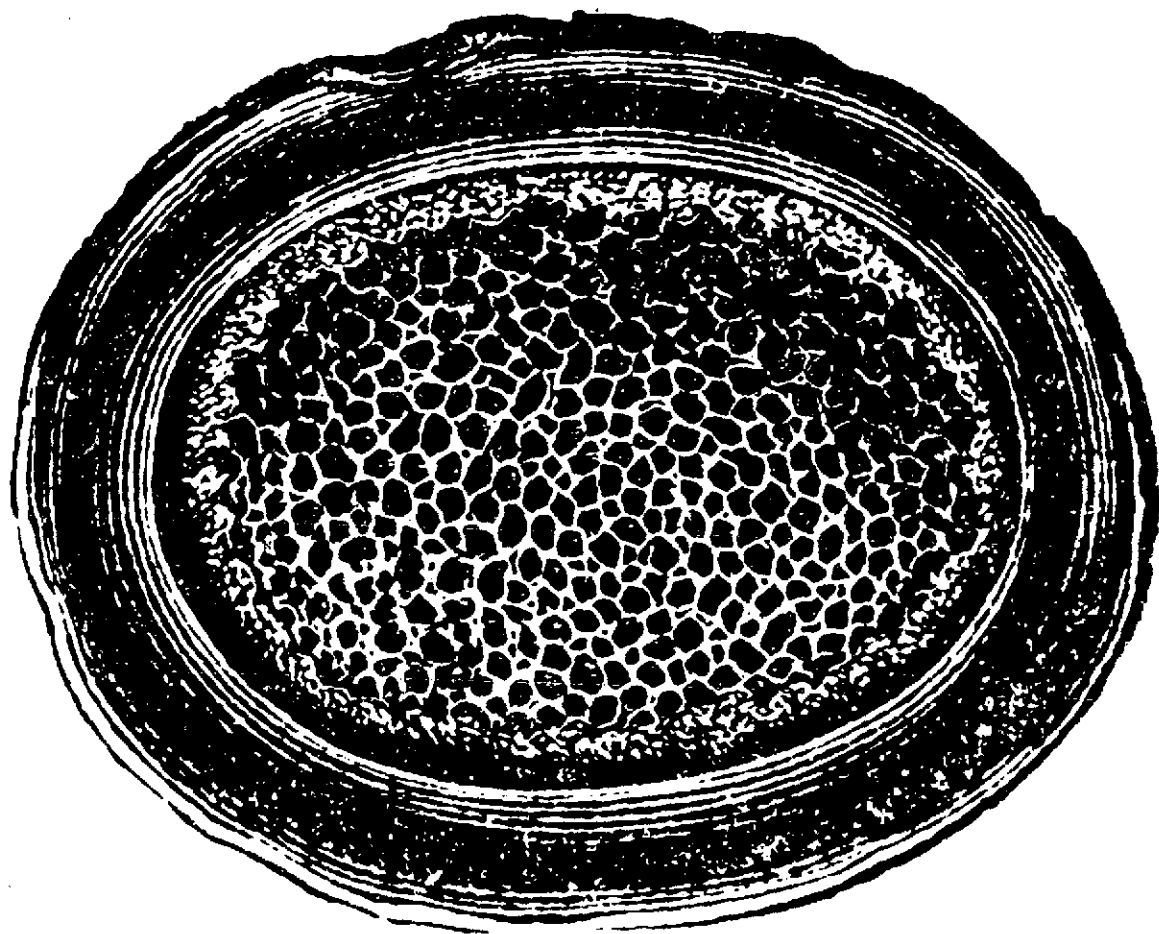
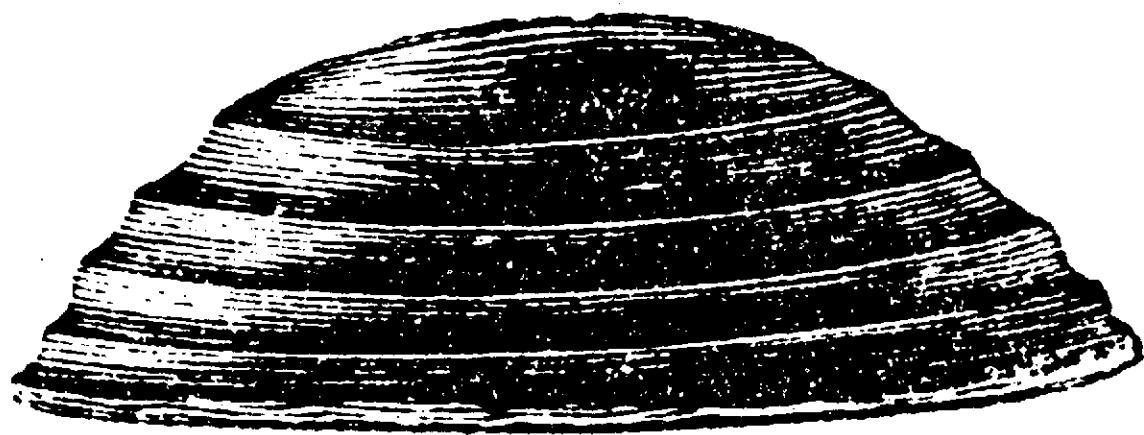


Fig. 1-2 |

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Fig. 1-2

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TEKTITE STREWN FIELDS

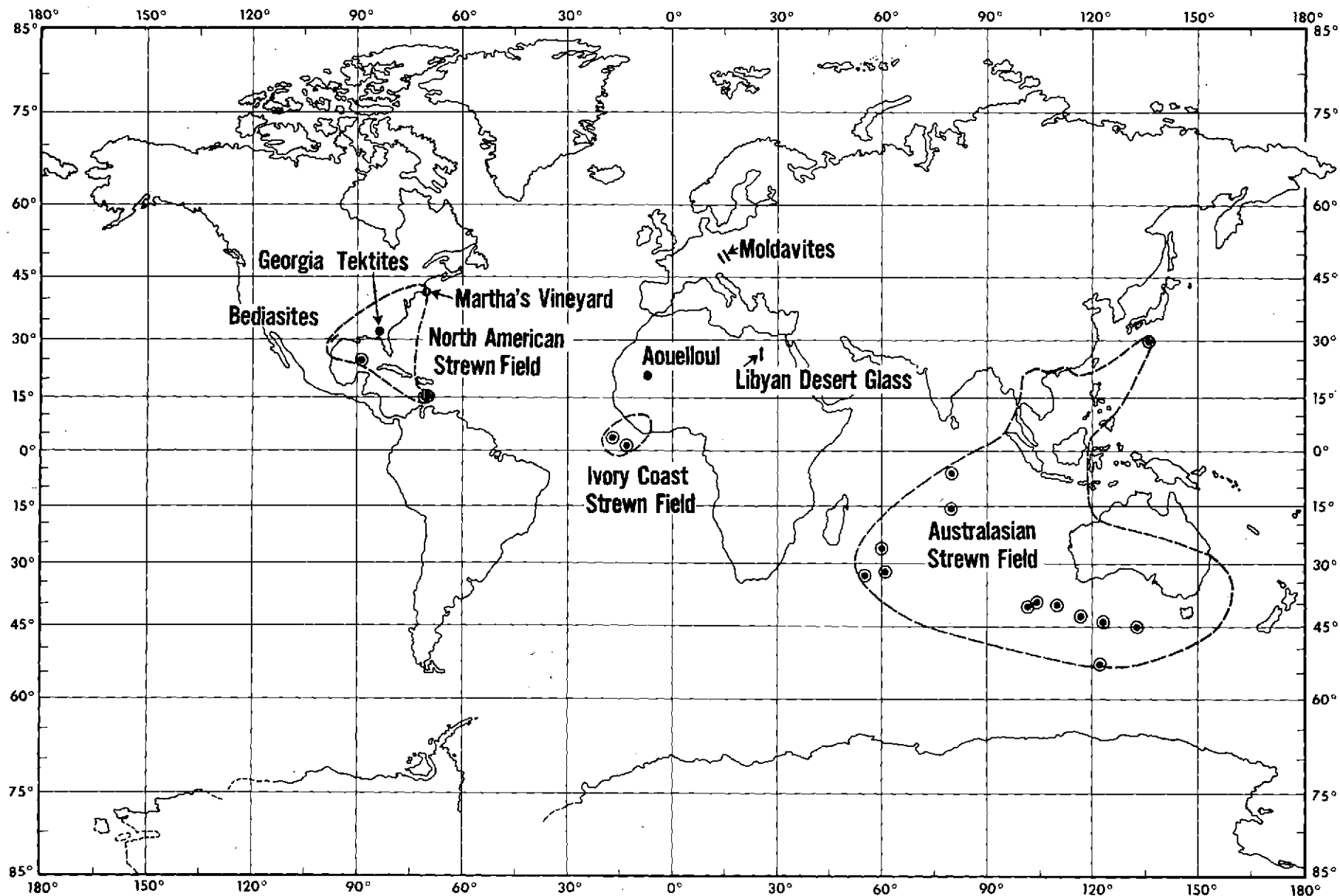


Fig. 2-1

J.A.O'Keefe

Fig. 2-1

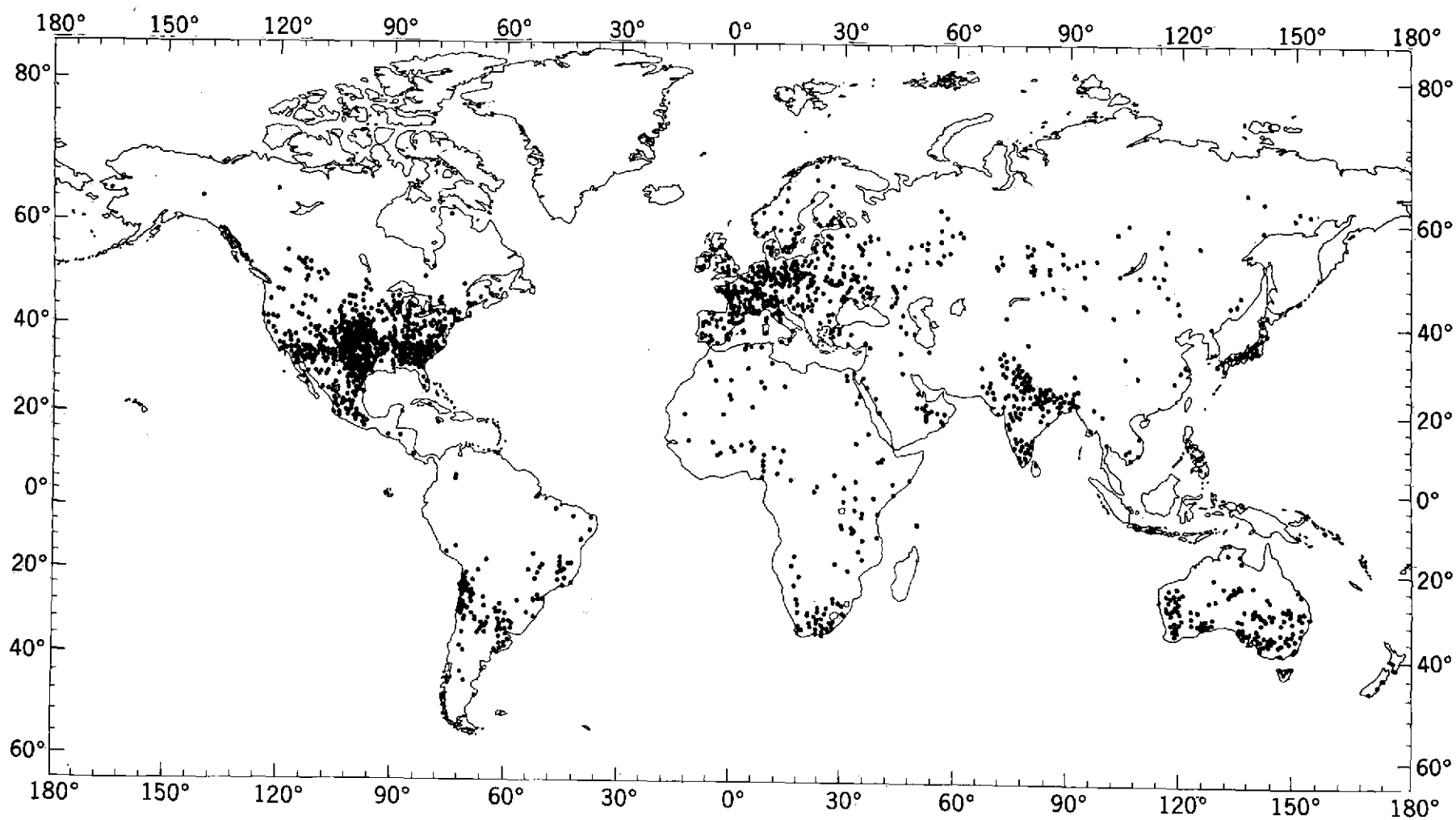


Fig. 2-2

J.A.O'Keefe

Fig. 2-2

The Australasian Strewn Field

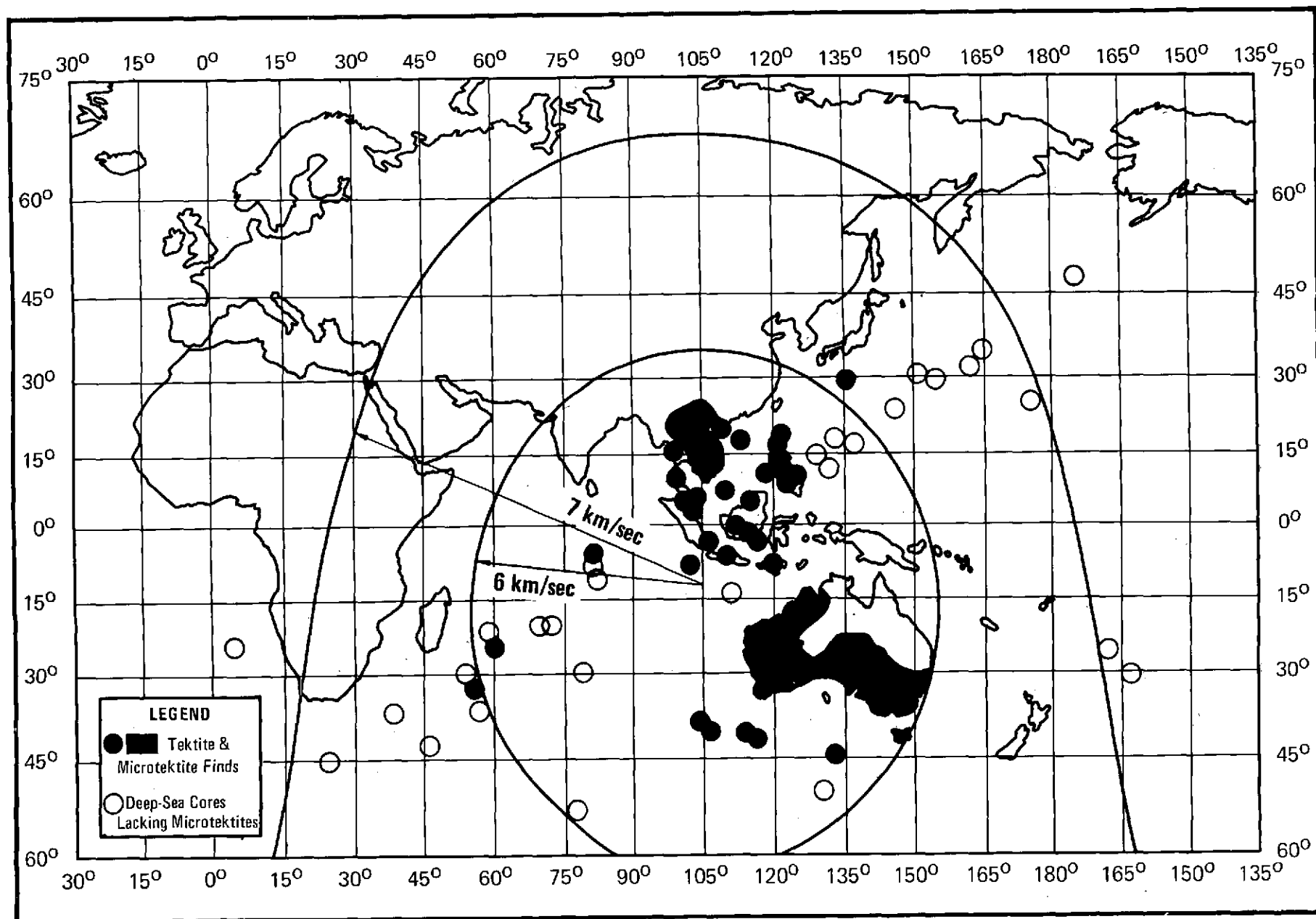


Fig. 2-3

J.A.O'Keefe

Fig. 2-3

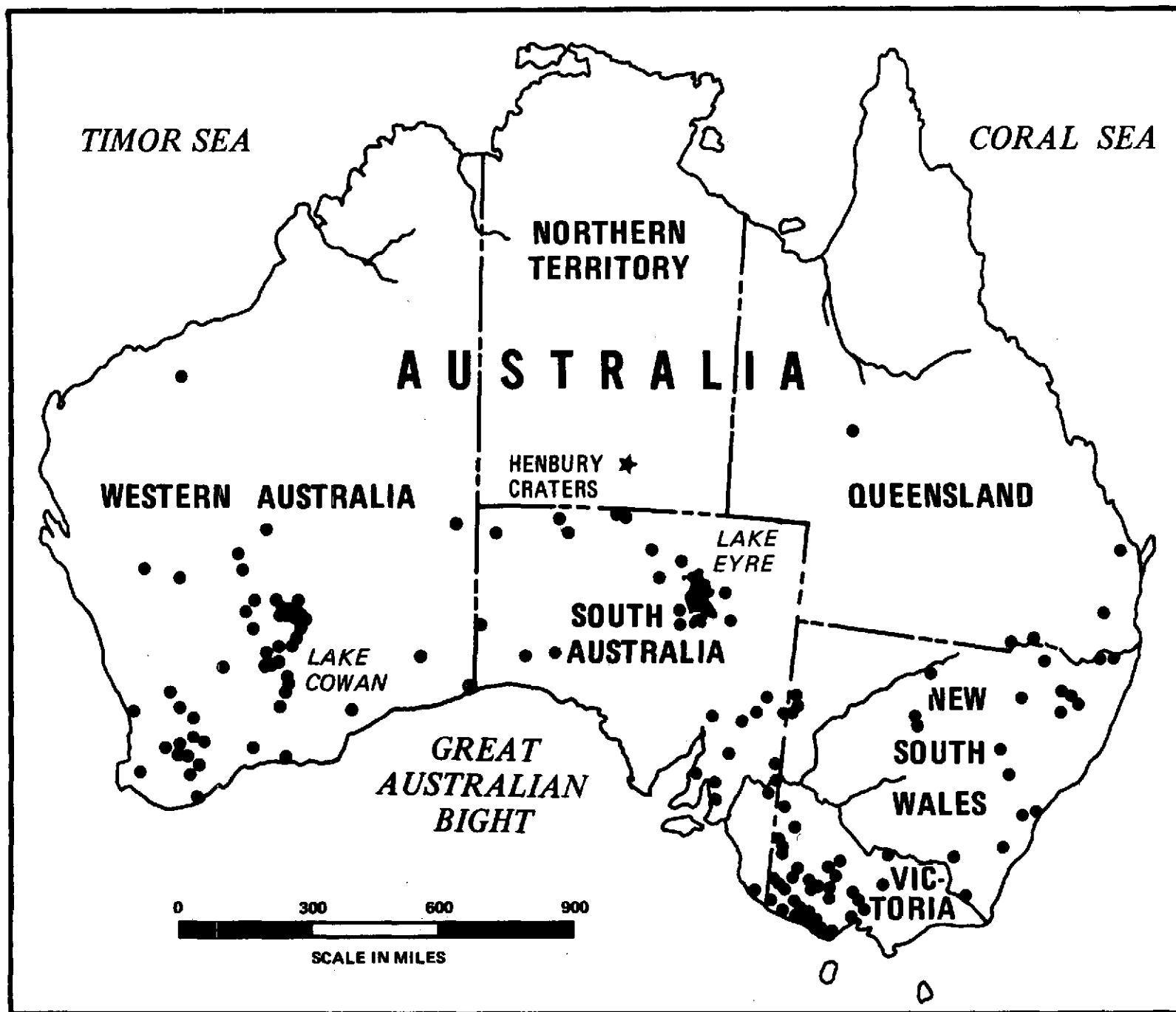


Fig. 3.—Distribution of australites modified from Baker (1959)

J.A.O'Keefe

Fig. 2-4



Fig. 5.—Distribution of indomalaysianites

J.A.O'Keefe

Fig. 2-5



FIG. 7.—Distribution of indochinities

Fig. 2-6 |

J.A.O'Keefe

Fig. 2-6

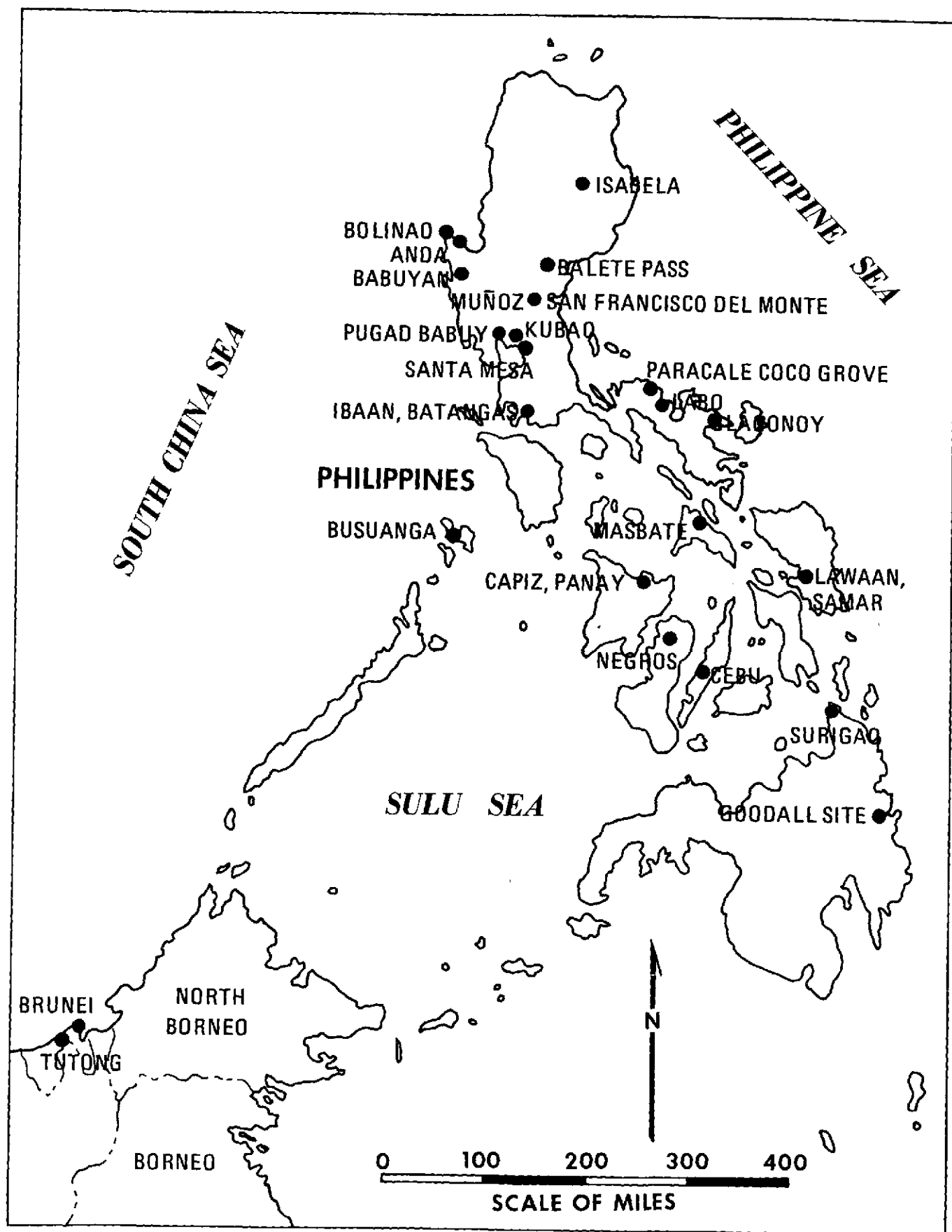


FIG. 8.- Distribution of philippinites, Barnes & Beyer

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Fig. 2-7

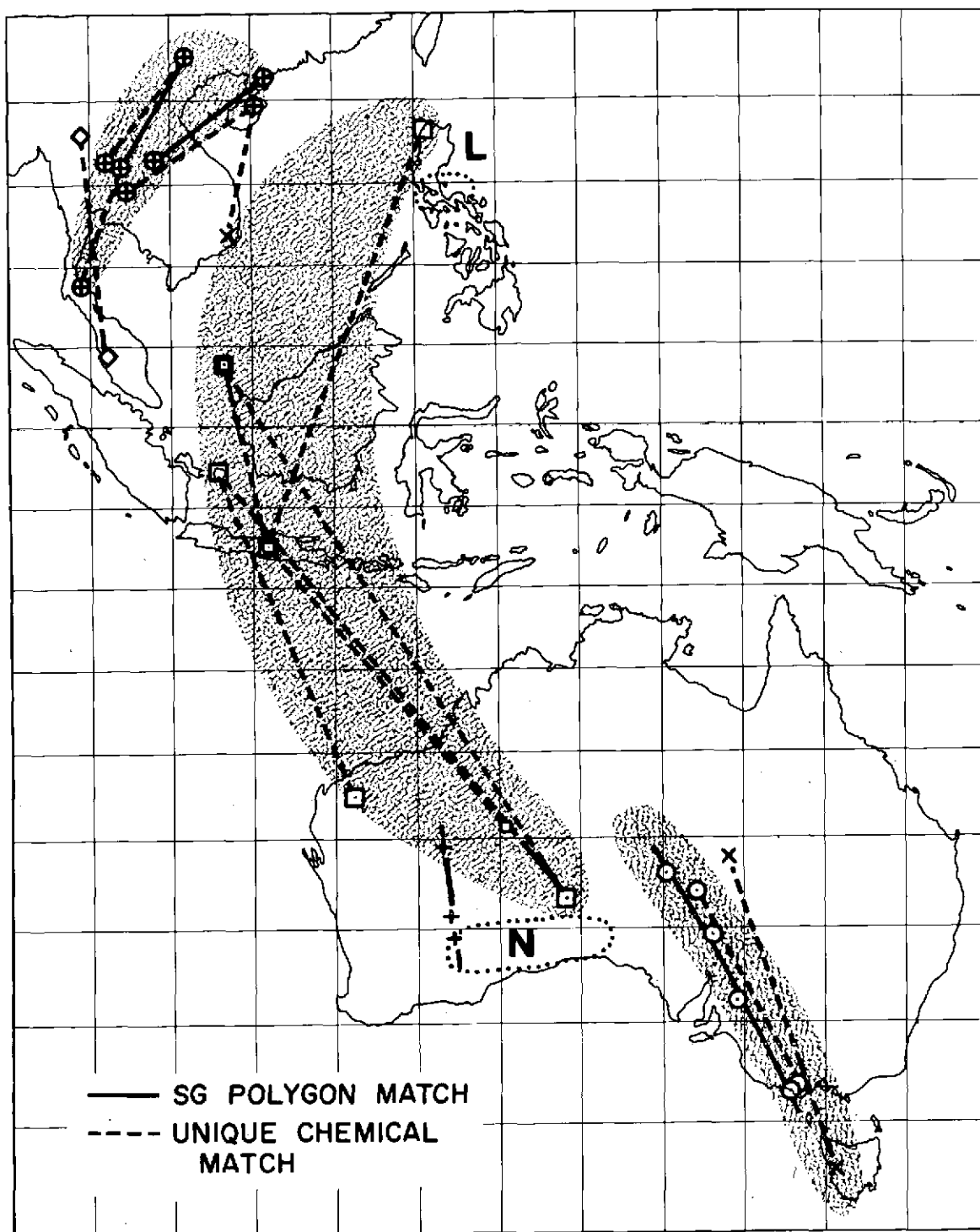


Fig. 2-8

J.A.O'Keefe

Fig. 2-8

THE MACEDON - DARWIN GLASS STREWN FIELD

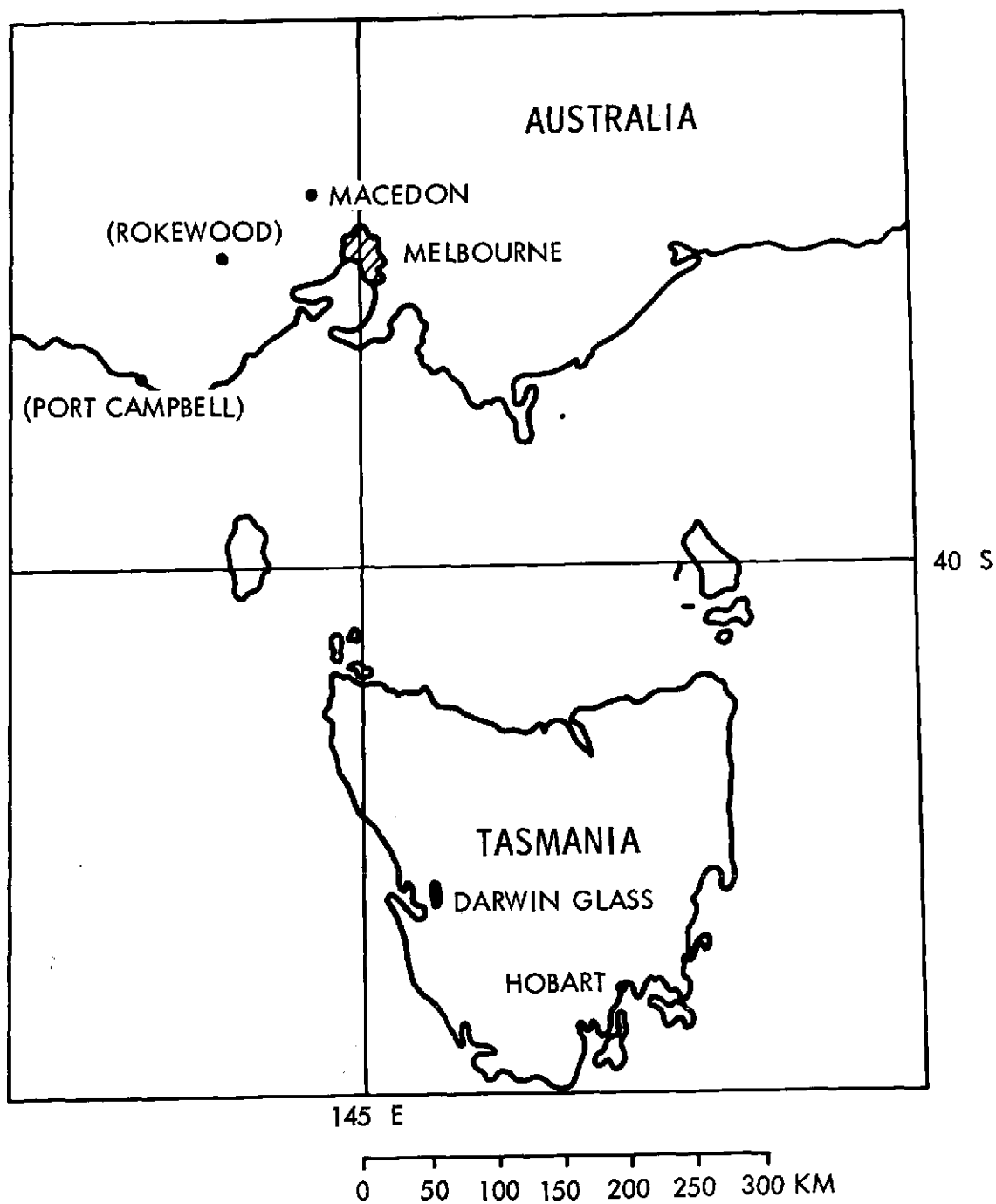


Fig. 2-9

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Fig. 2-9

THE IVORY COAST STREWN FIELD

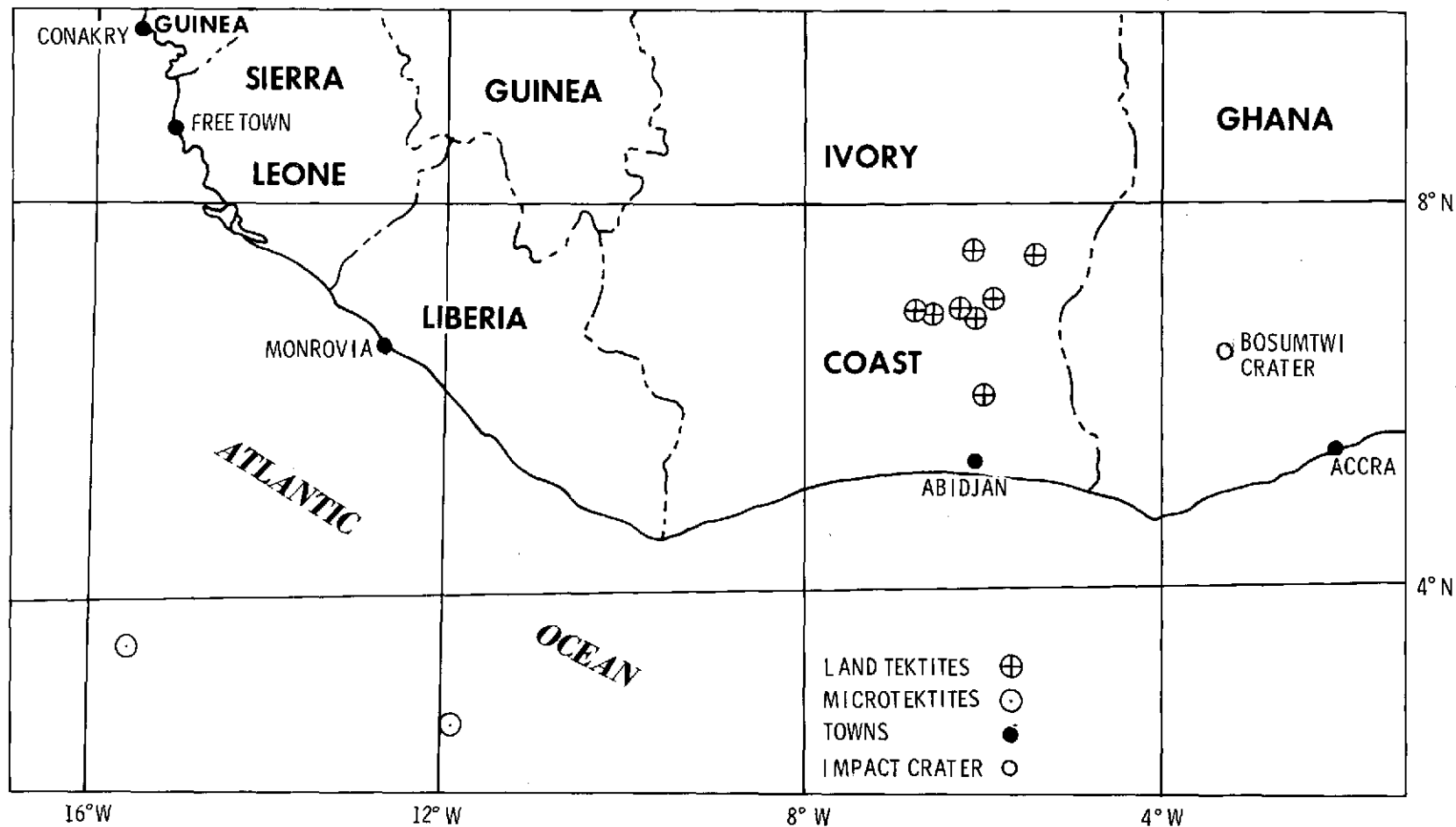


Fig. 2-10

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Fig. 2-10

The moldavite (Czechoslovakian) strewnfield

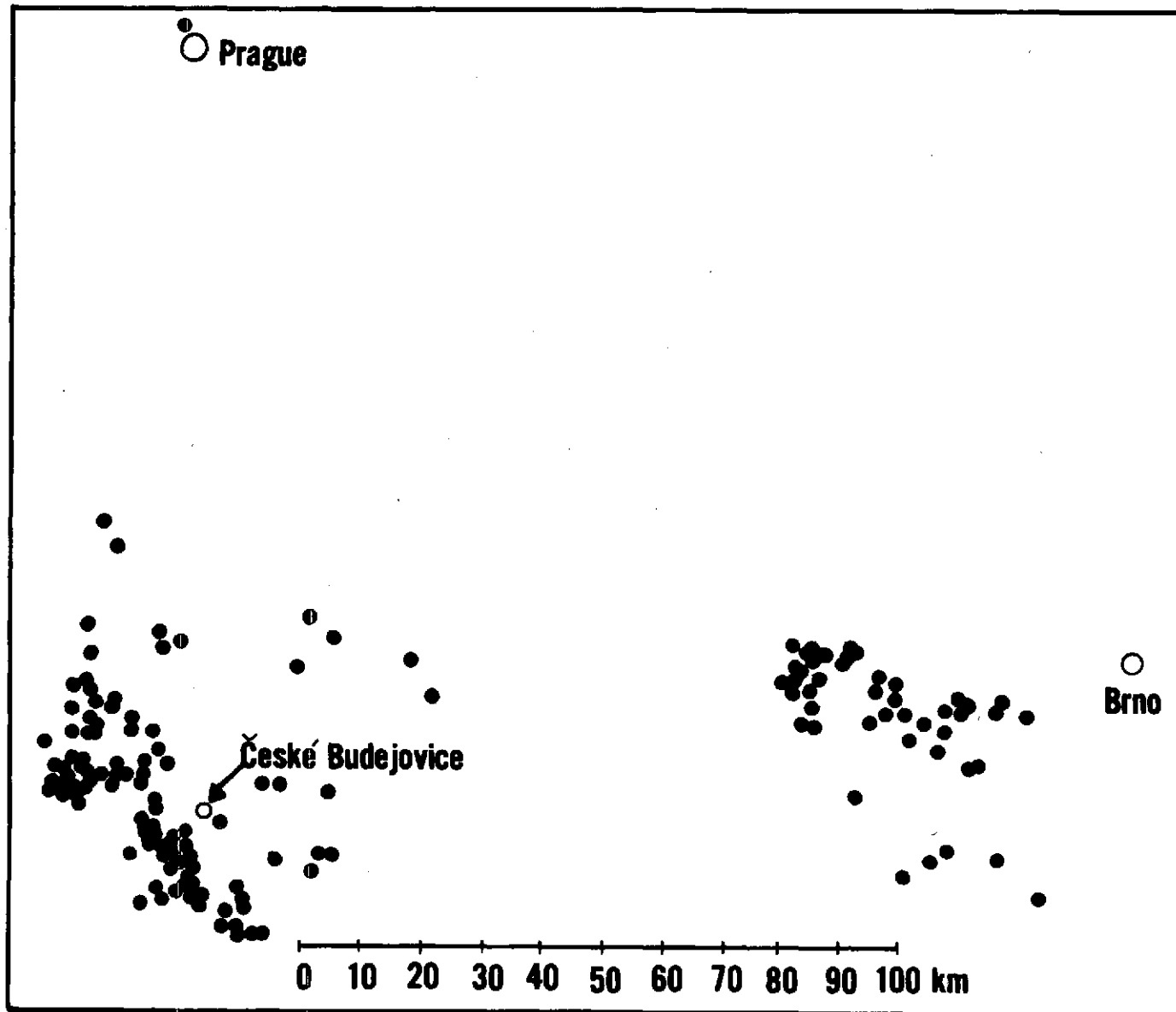


Fig. 2-11

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Fig. 2-11

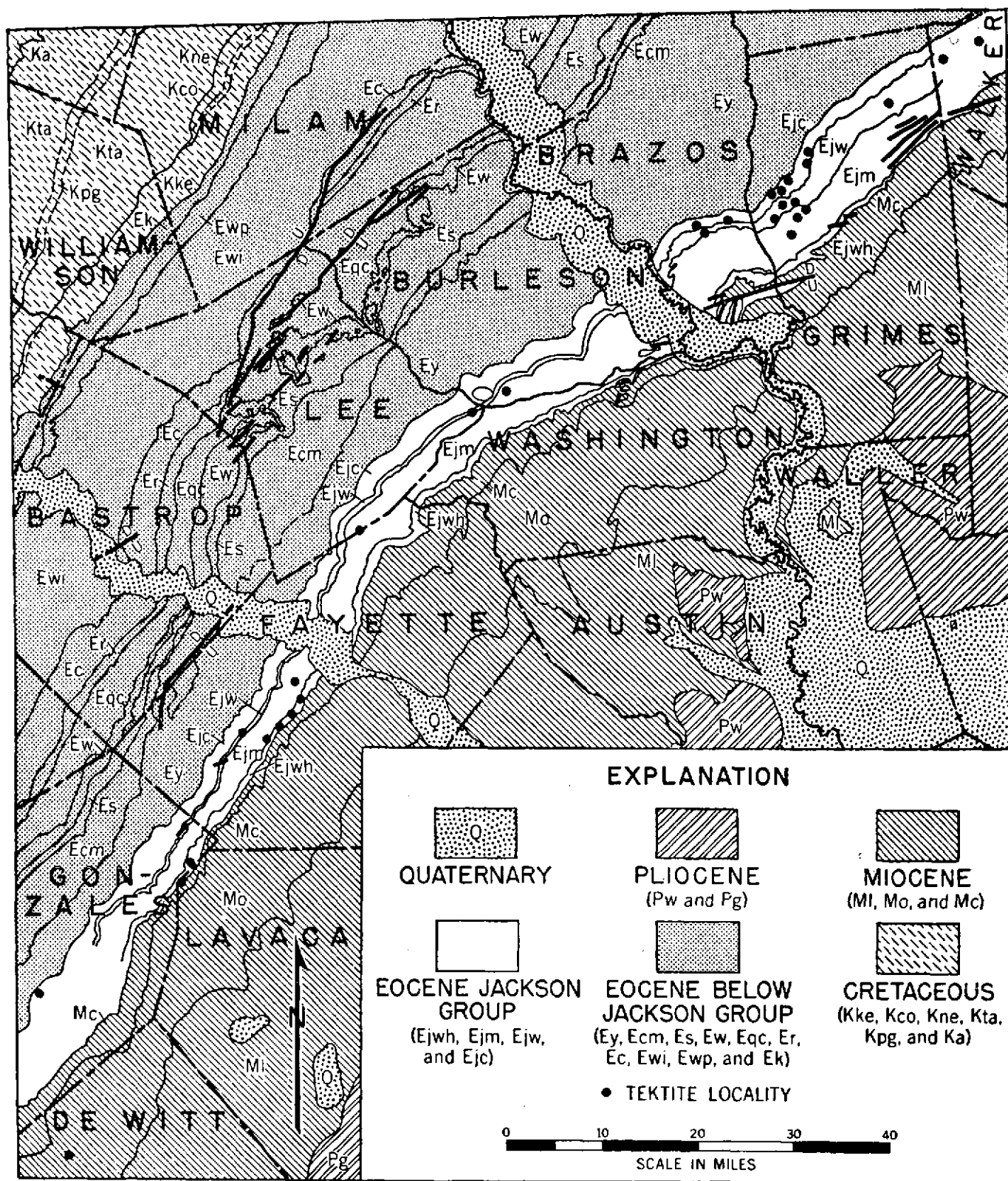


FIG. 9.—Distribution of bediasites in relation to geologic formations

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Fig. 2-12

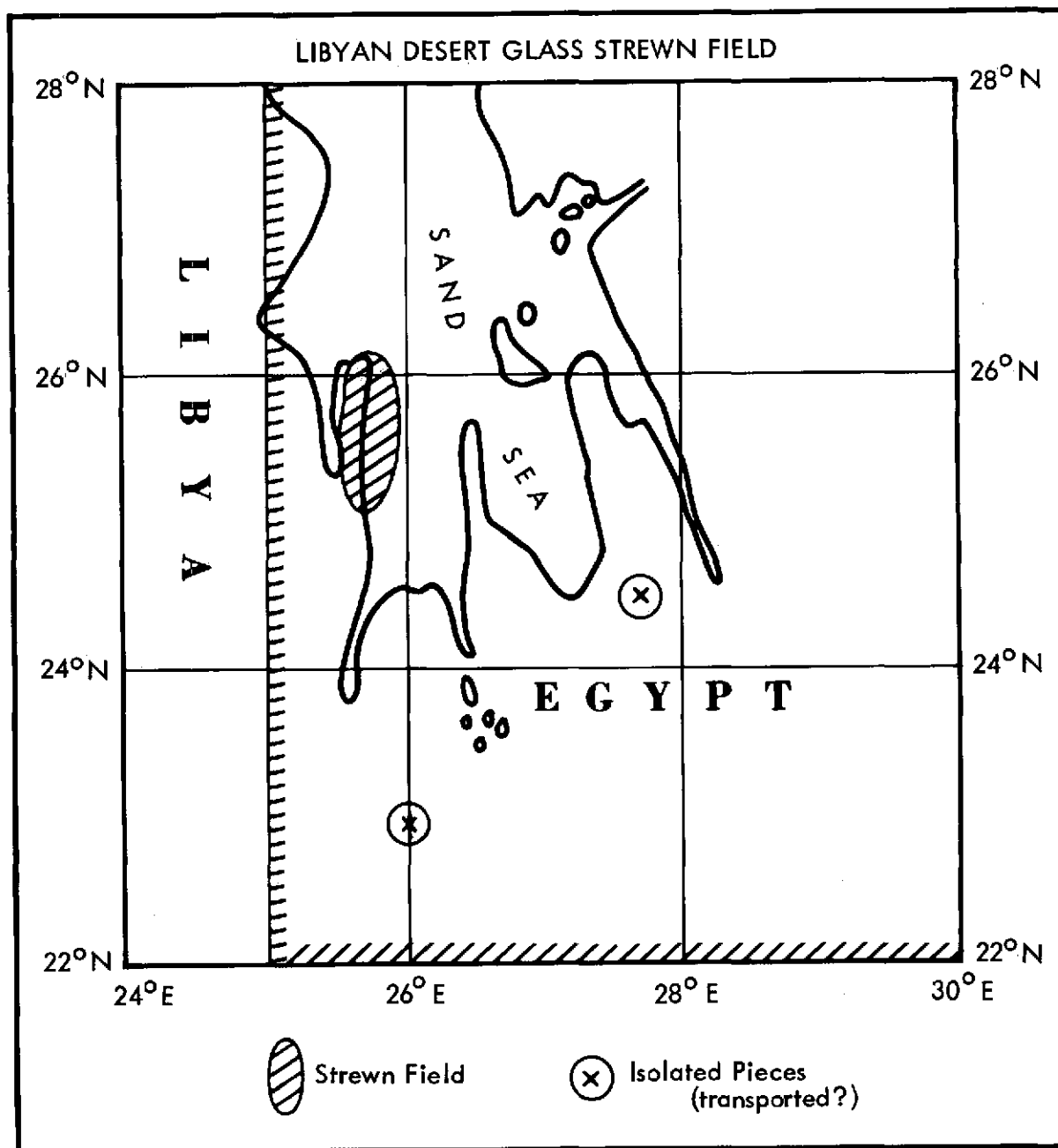


Fig. 2-13

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Fig. 2-13

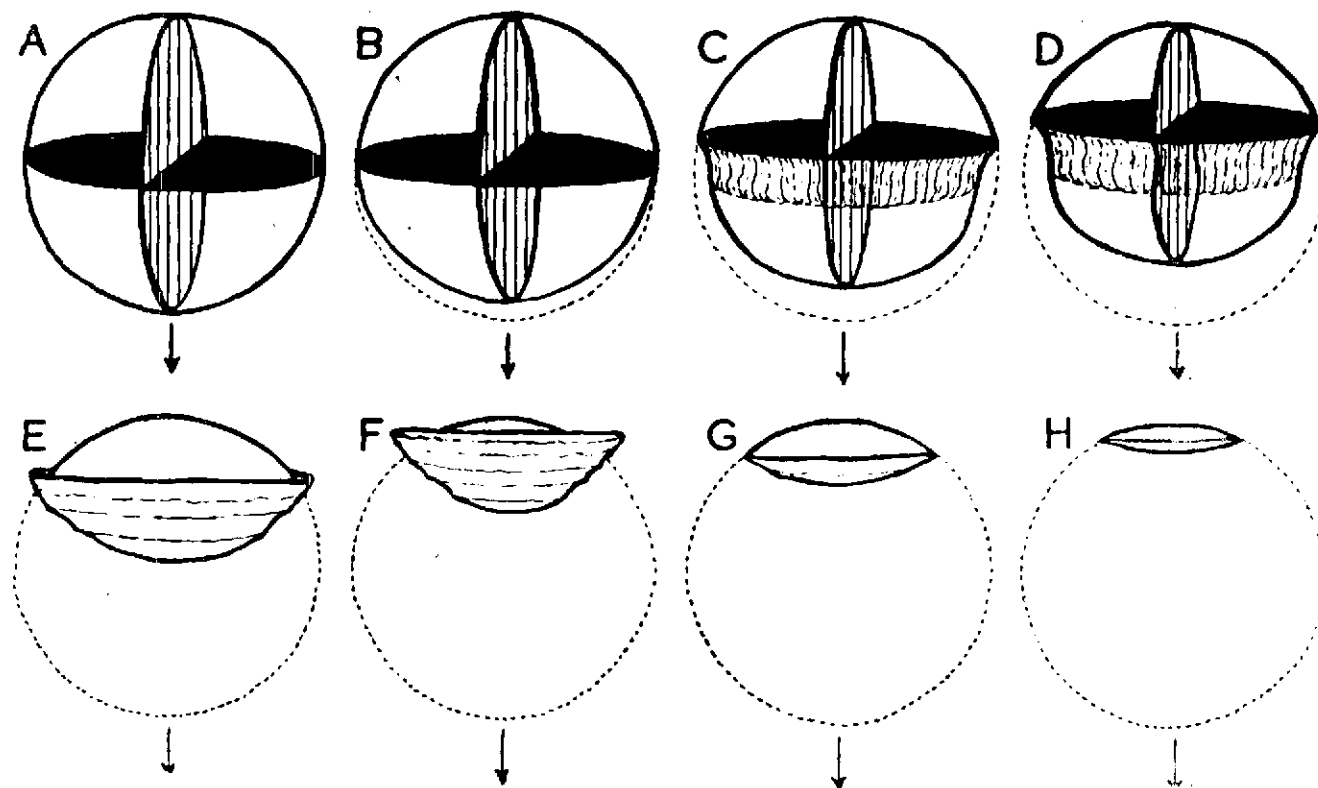


Fig. 3-1

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Fig. 3-1

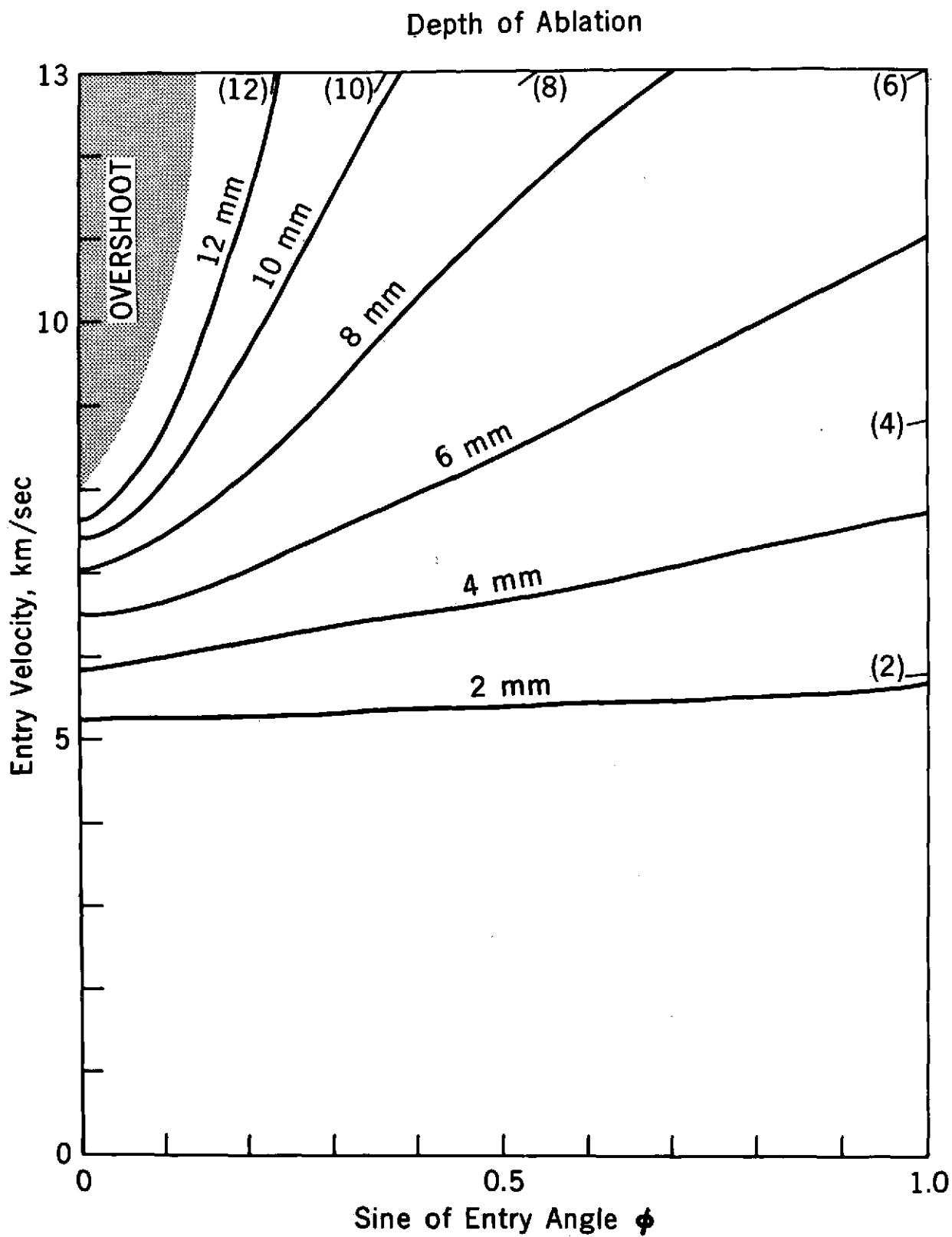


Fig. 3-2

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Fig. 3-2

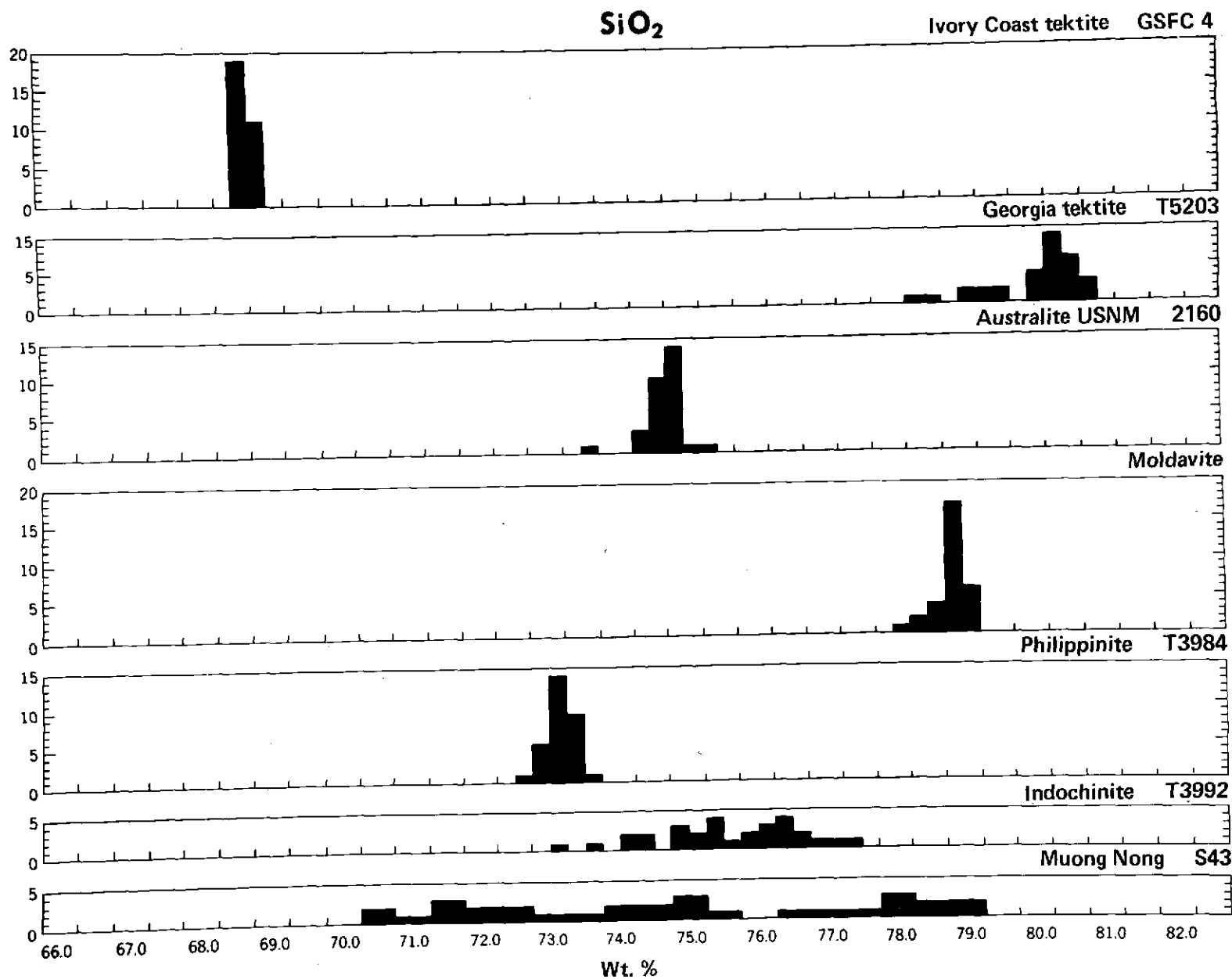


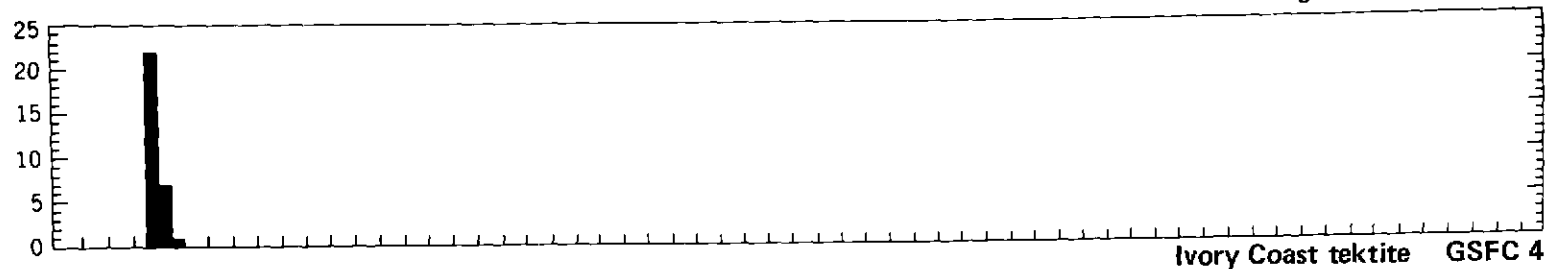
Fig. 4-1

J.A.O'Keefe

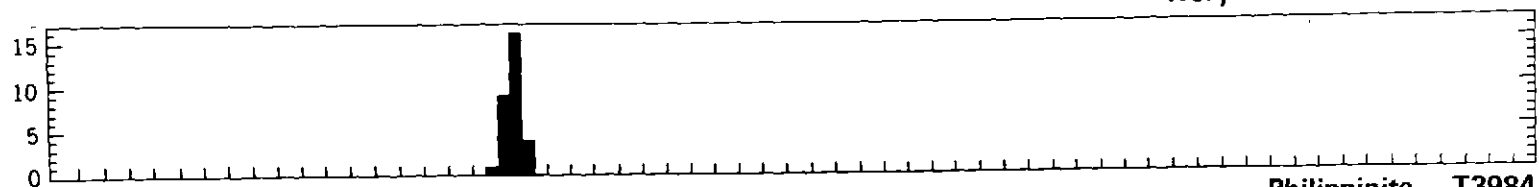
Fig. 4-1

CaO

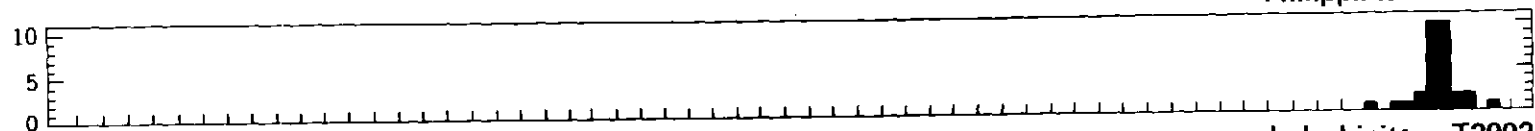
Georgia tektite T5203



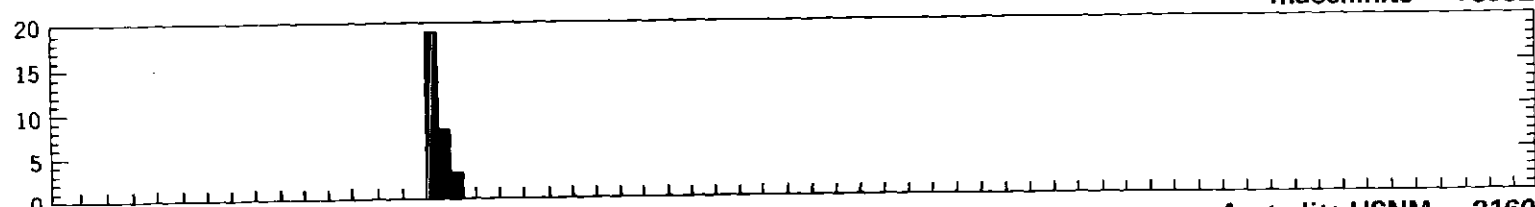
Ivory Coast tektite GSFC 4



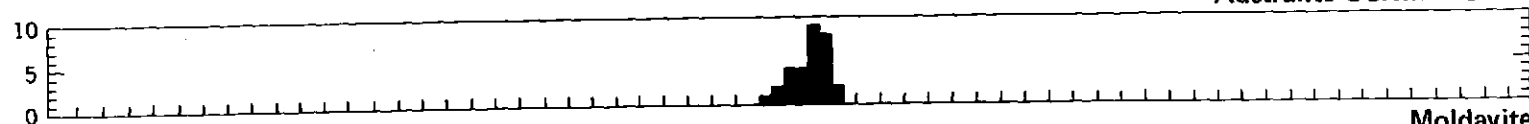
Philippinite T3984



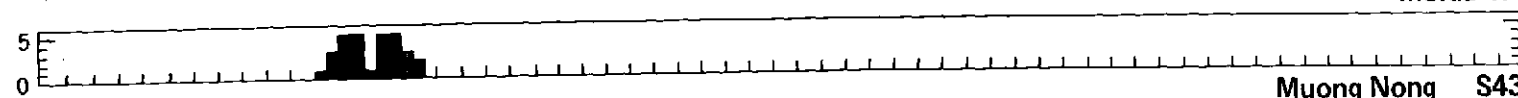
Indochinite T3992



Australite USNM 2160



Moldavite



Muong Nong S43

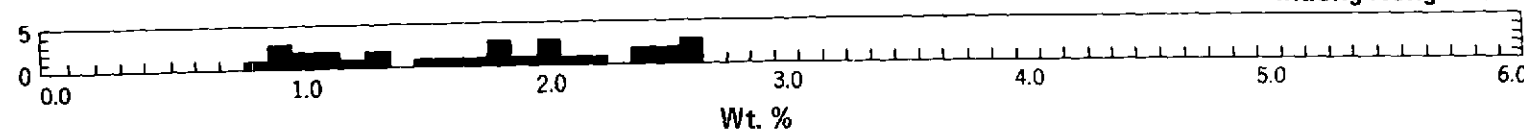


Fig. 4-2

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Fig. 4-2

MUONG NONG - 43

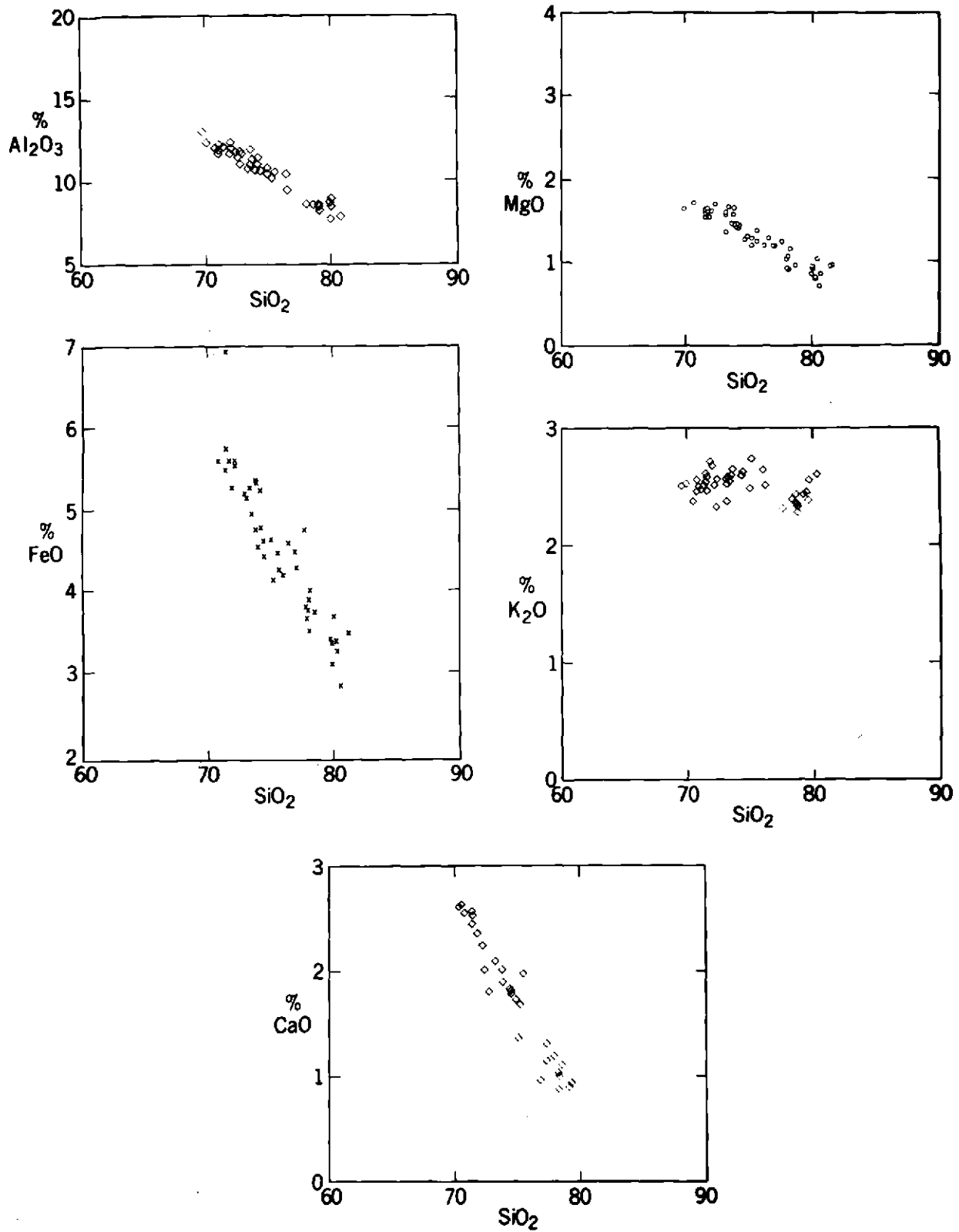


Fig. 4-3

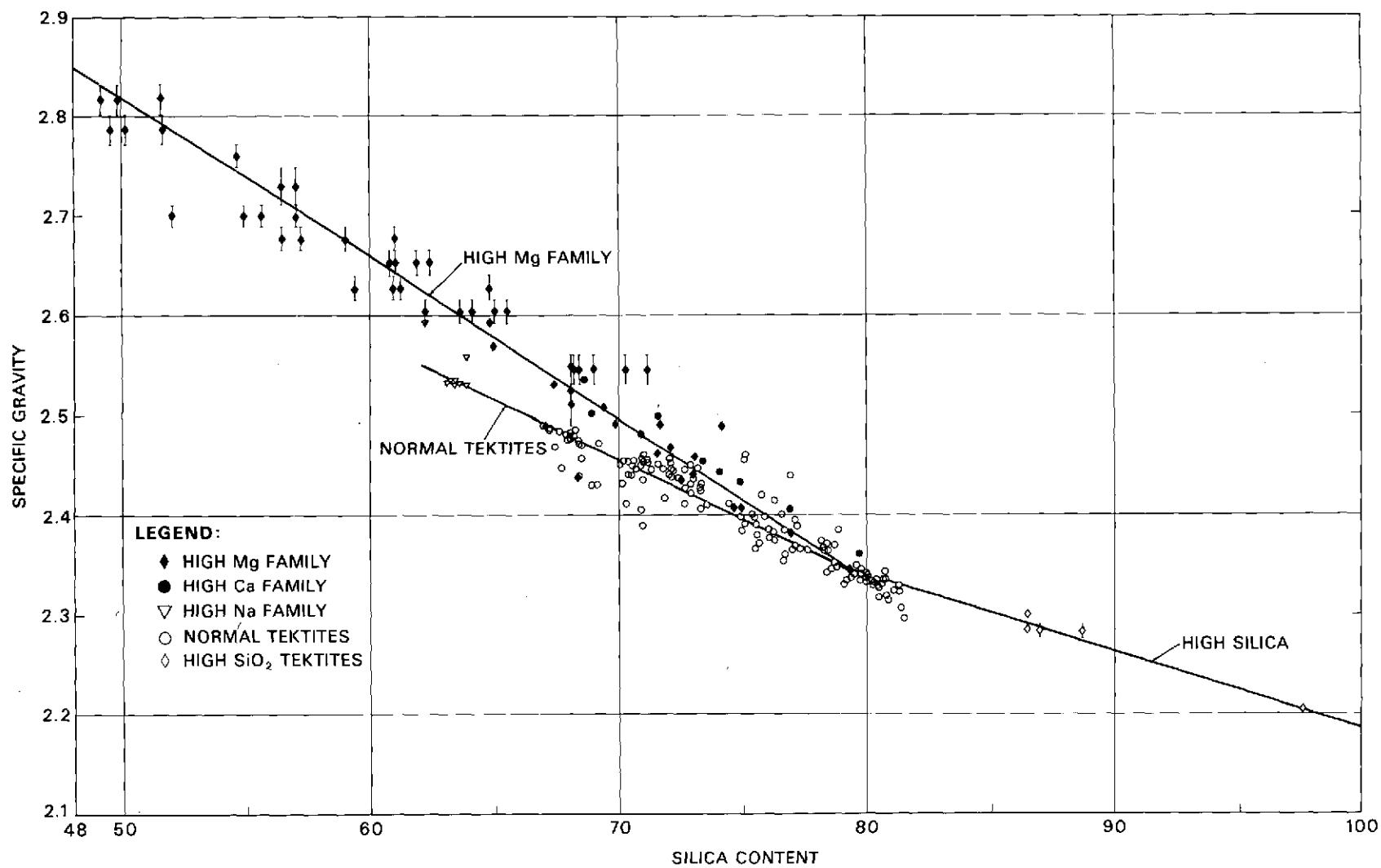


Fig. 5-1

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Fig. 5-1

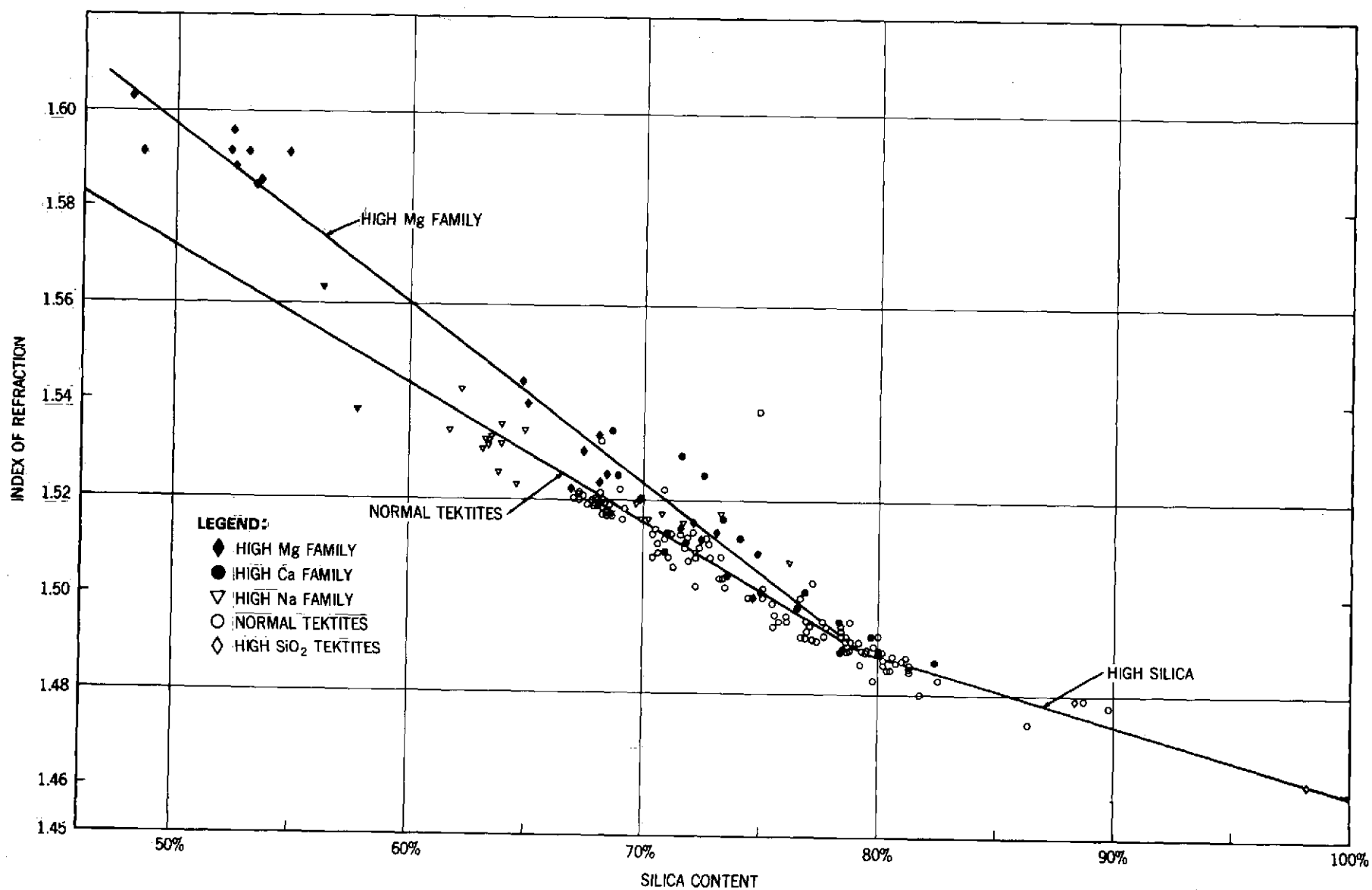


Fig. 5-2

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Fig. 5-2

Spectral transmittance of two tektites

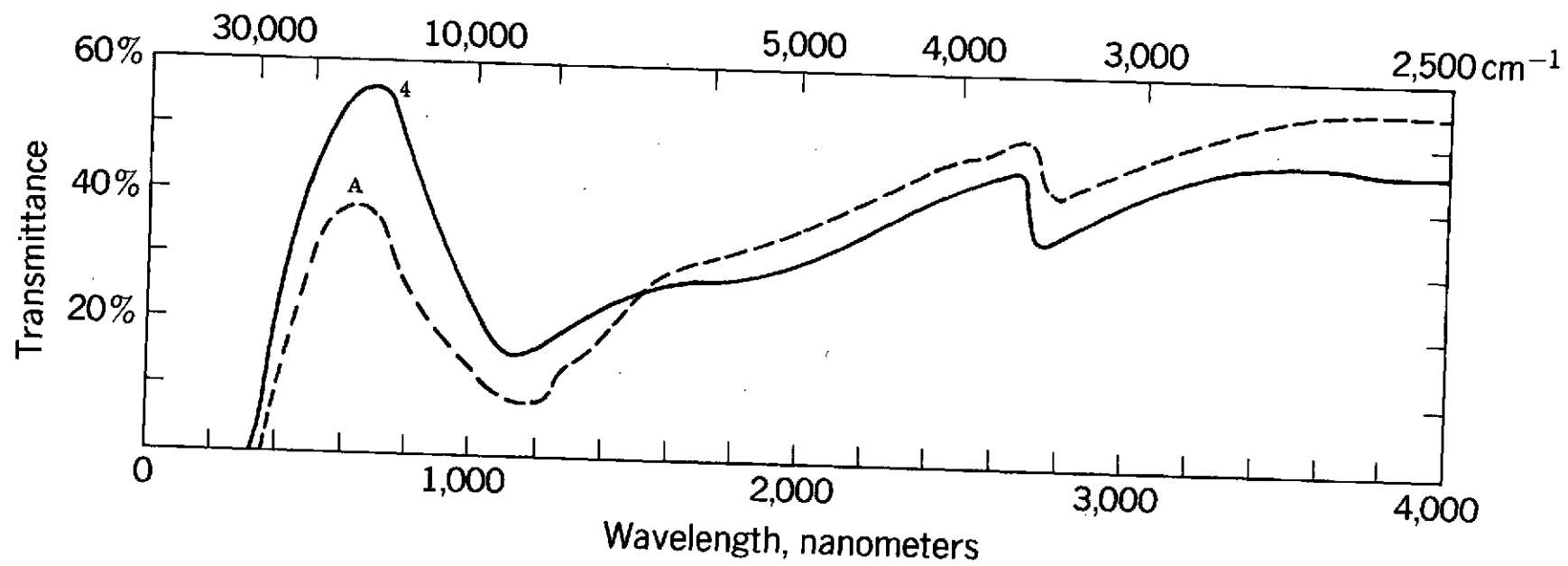


Fig. 5-3

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Fig. 5-3

MOLDAVITE GLASS, INFRARED TRANSMITTANCE

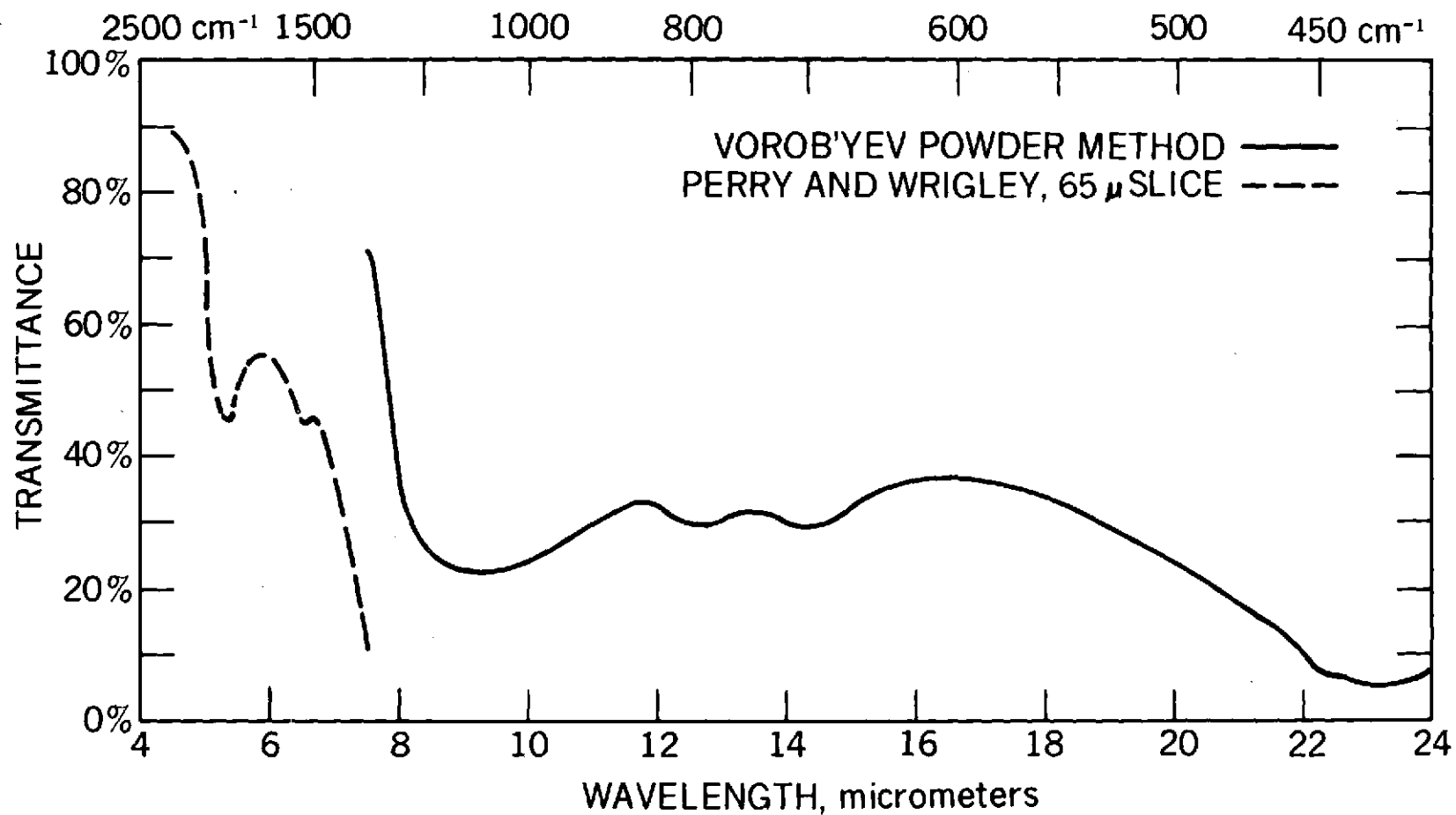


Fig. 5-4

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Fig. 5-4

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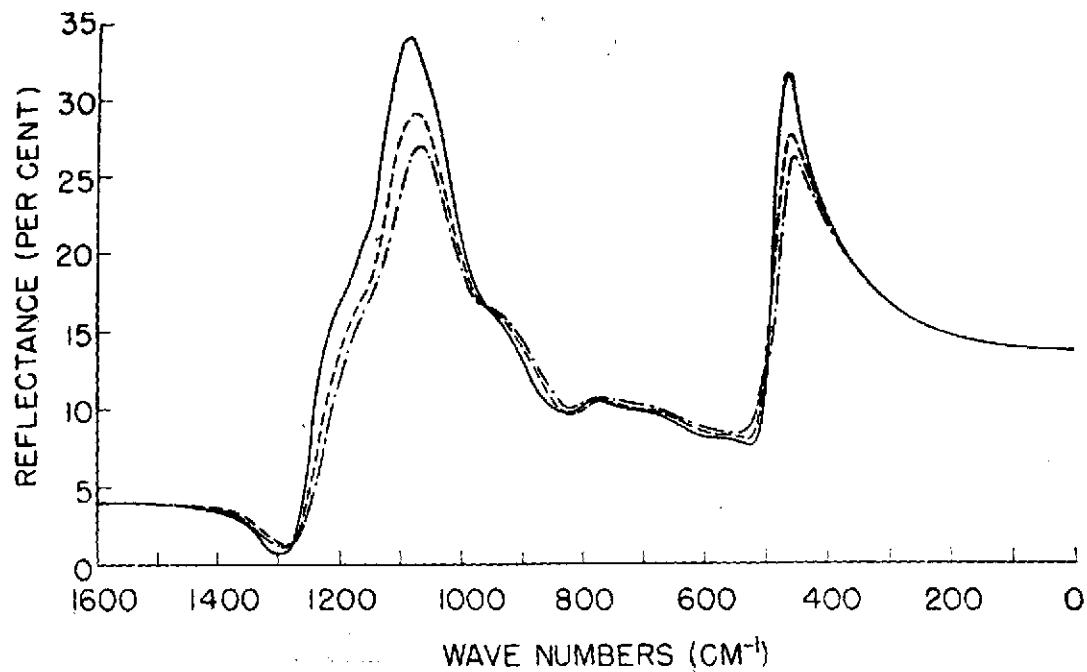


Fig. 5-5

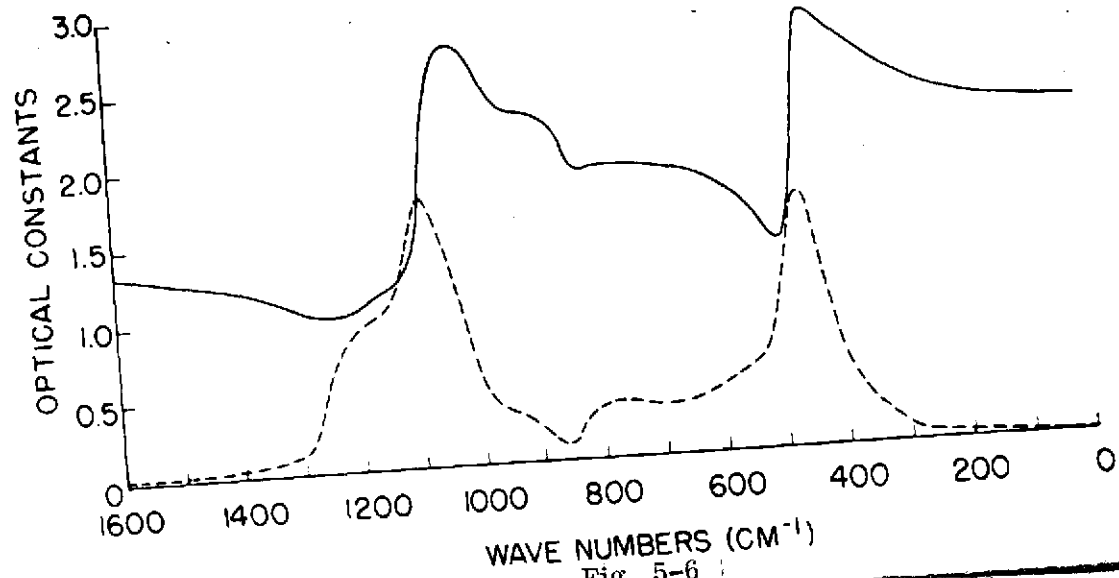


Fig. 5-6

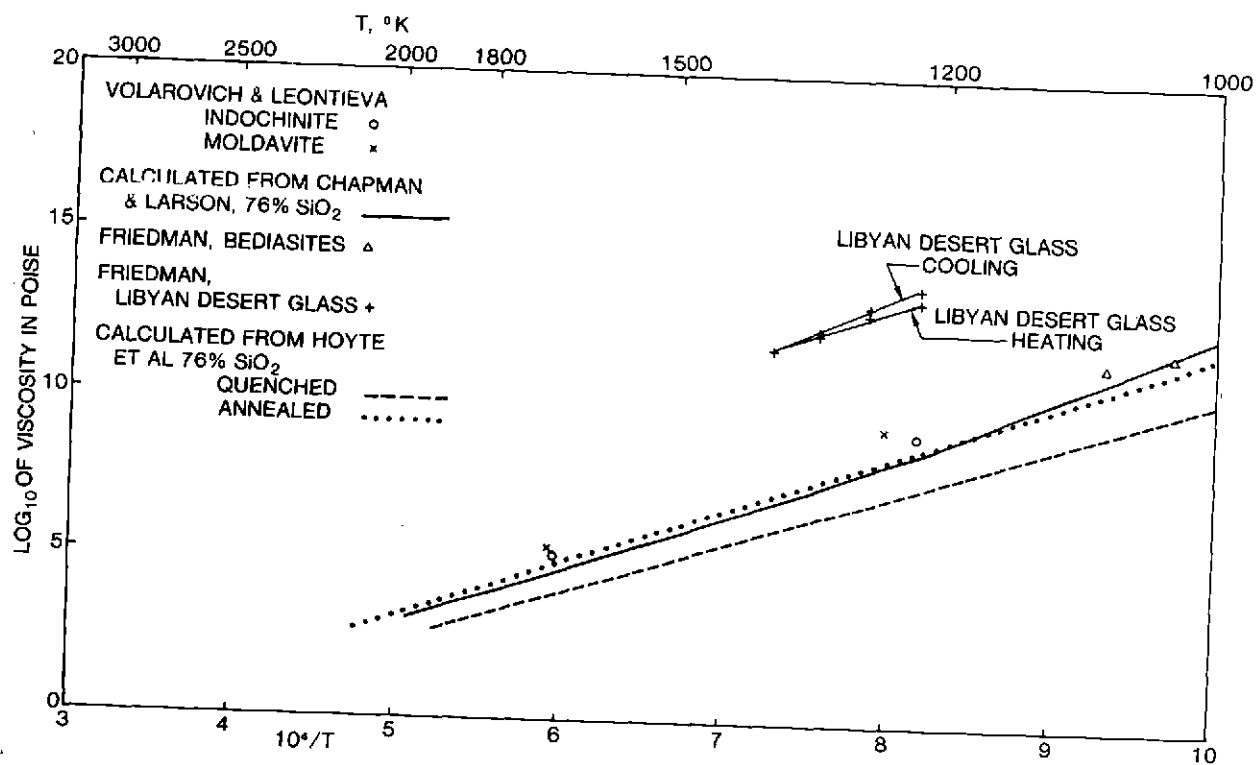


Fig. 5-7

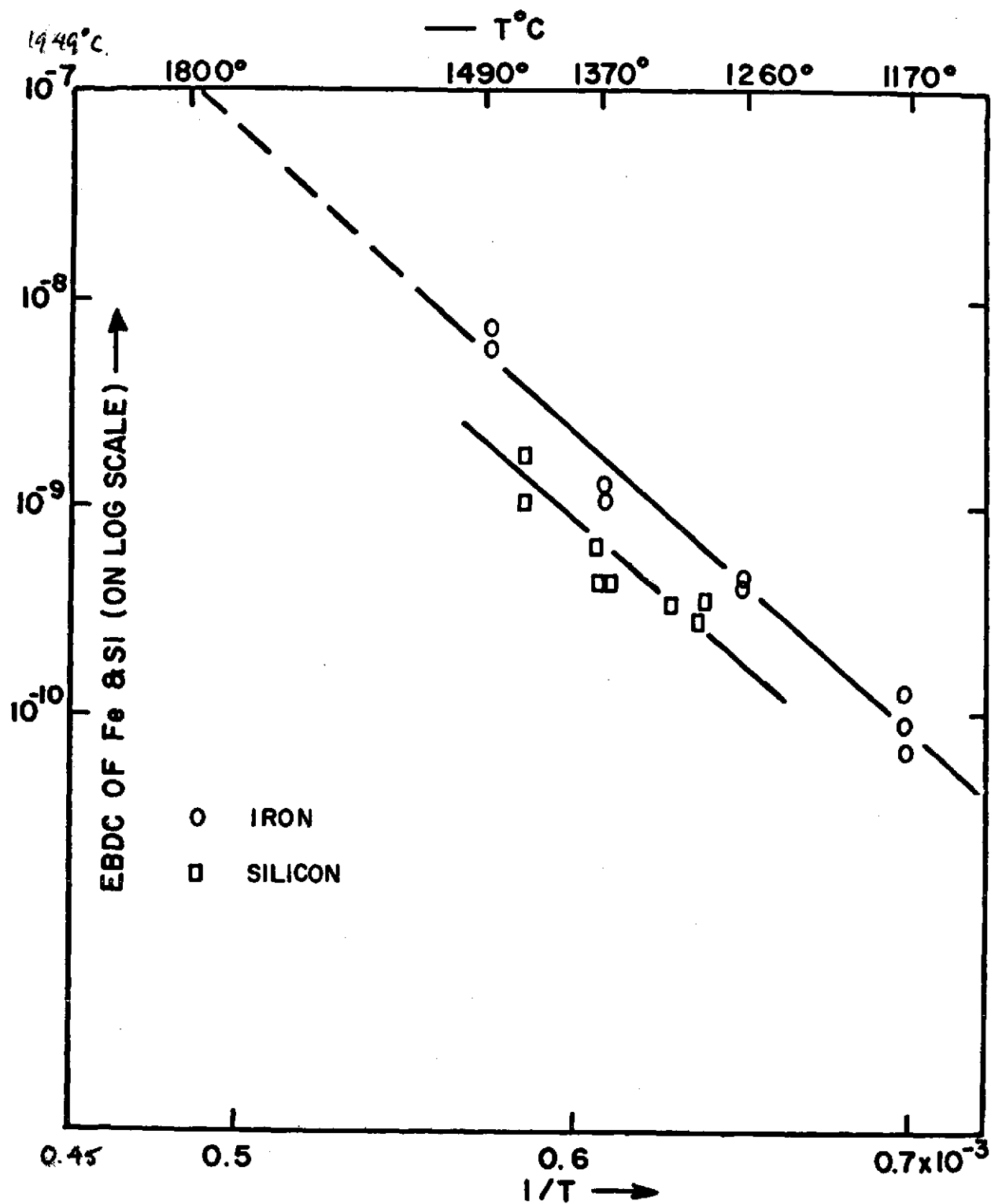


Fig. 5-8

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Fig. 5-8

EXCESS, NORMAL AUSTRALITE OVER G-1

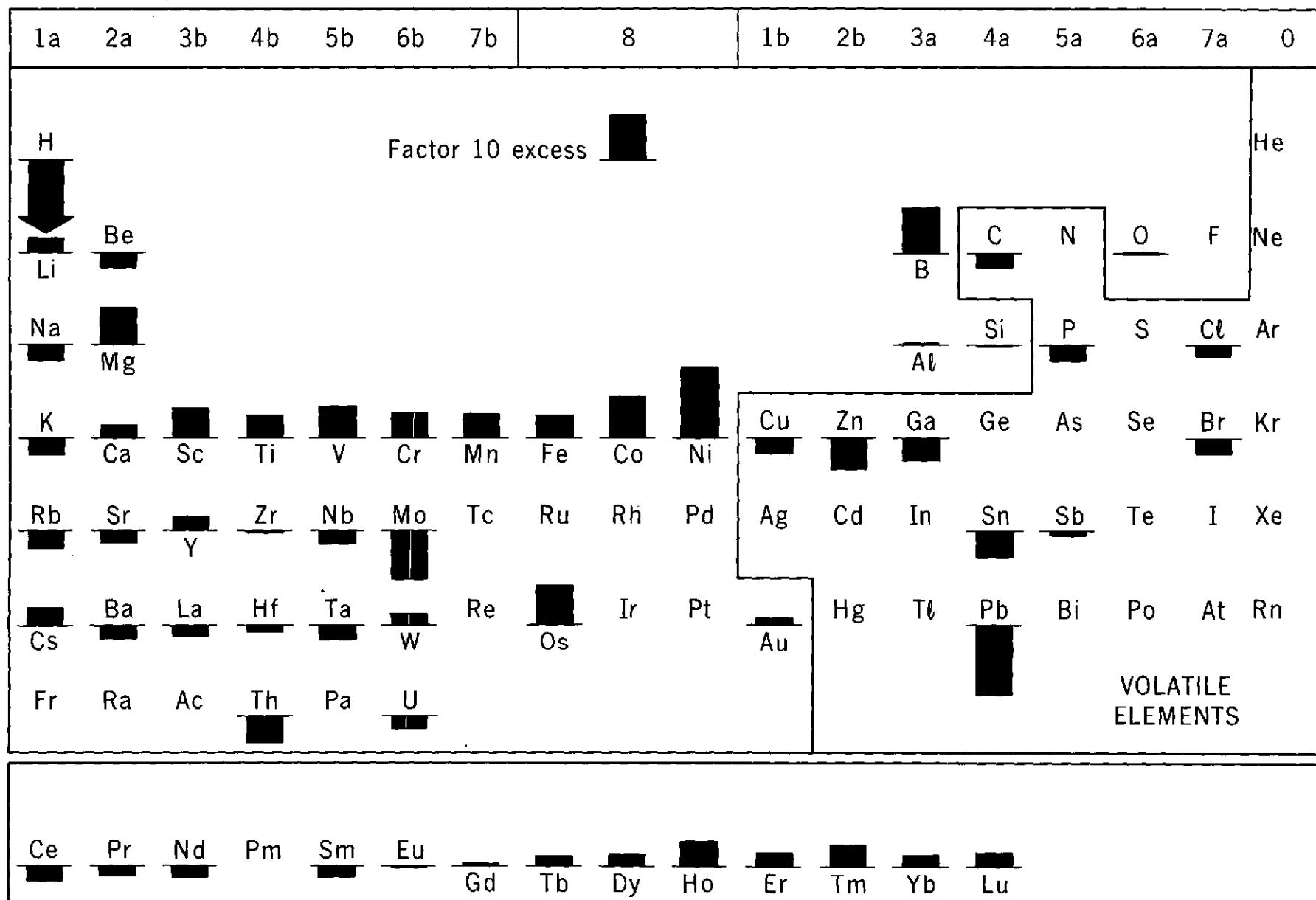


Fig. 6-1

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Fig. 6-1

EXCESS, NORMAL AUSTRALITE OVER W-1

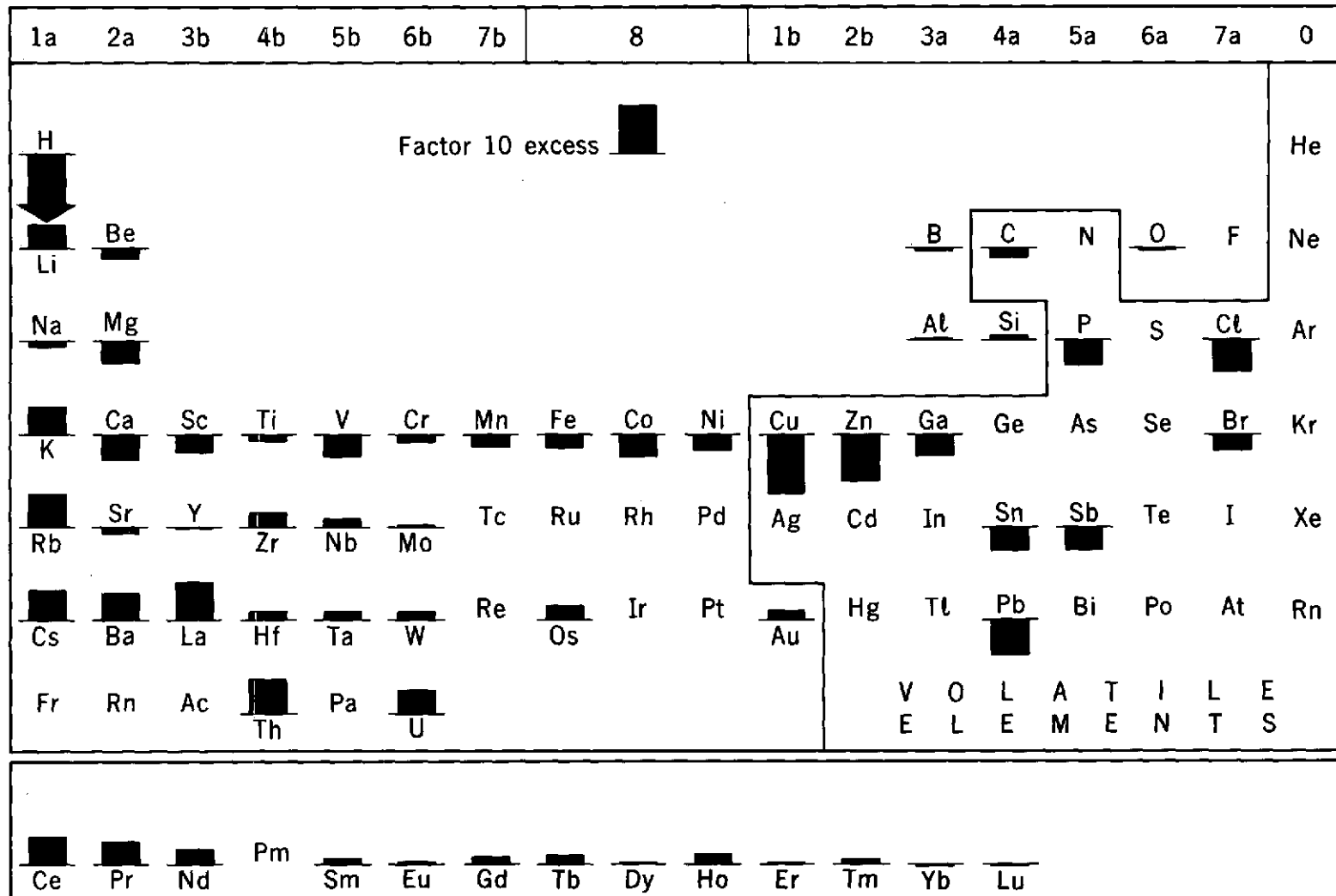


Fig. 6-2

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Fig. 6-2

EXCESS, NORMAL AUSTRALITE OVER AGV-1

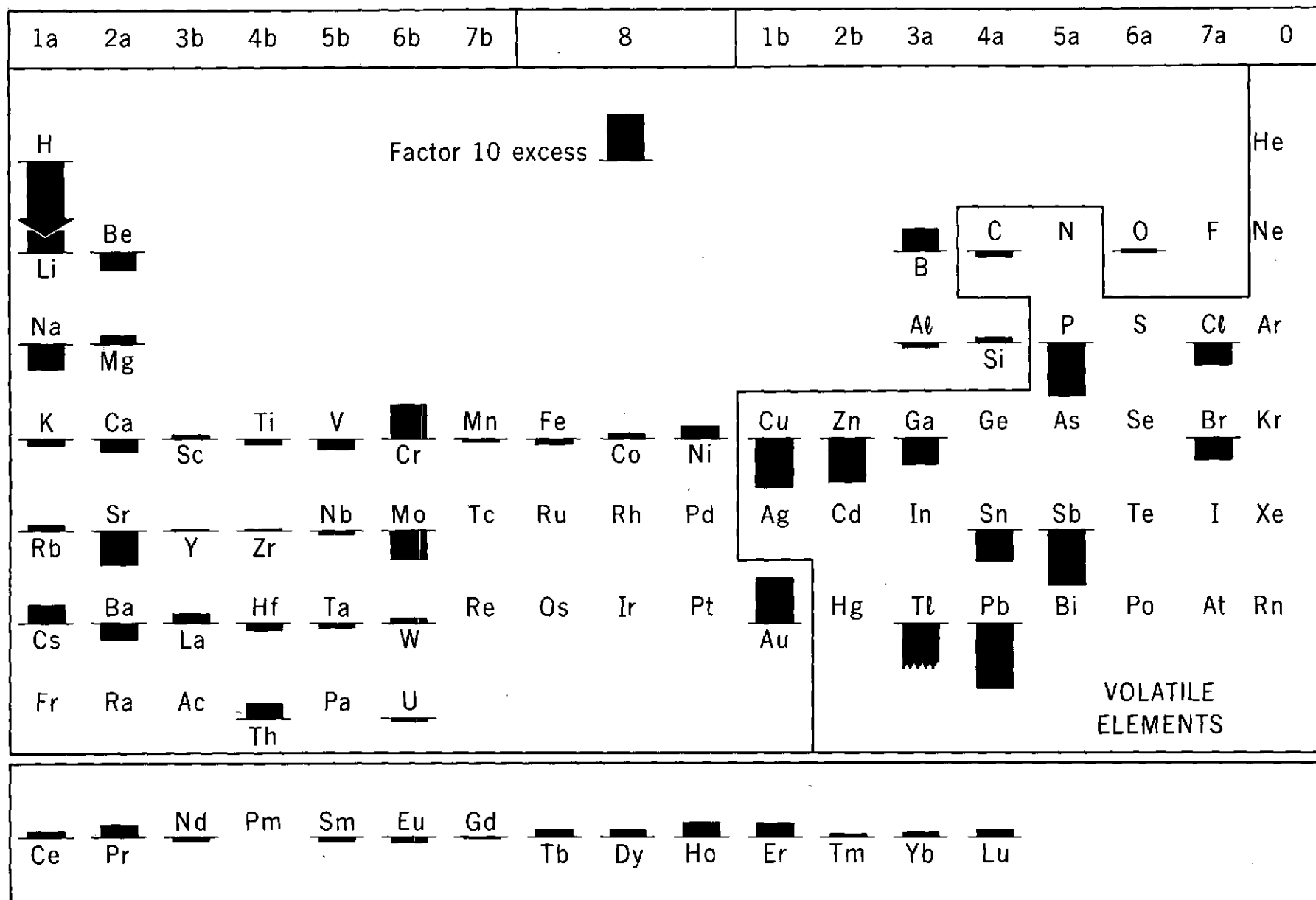


Fig. 6-3

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Fig.6-3

EXCESS, NORMAL AUSTRALITE OVER HENBURY SUBGRAYWACKE

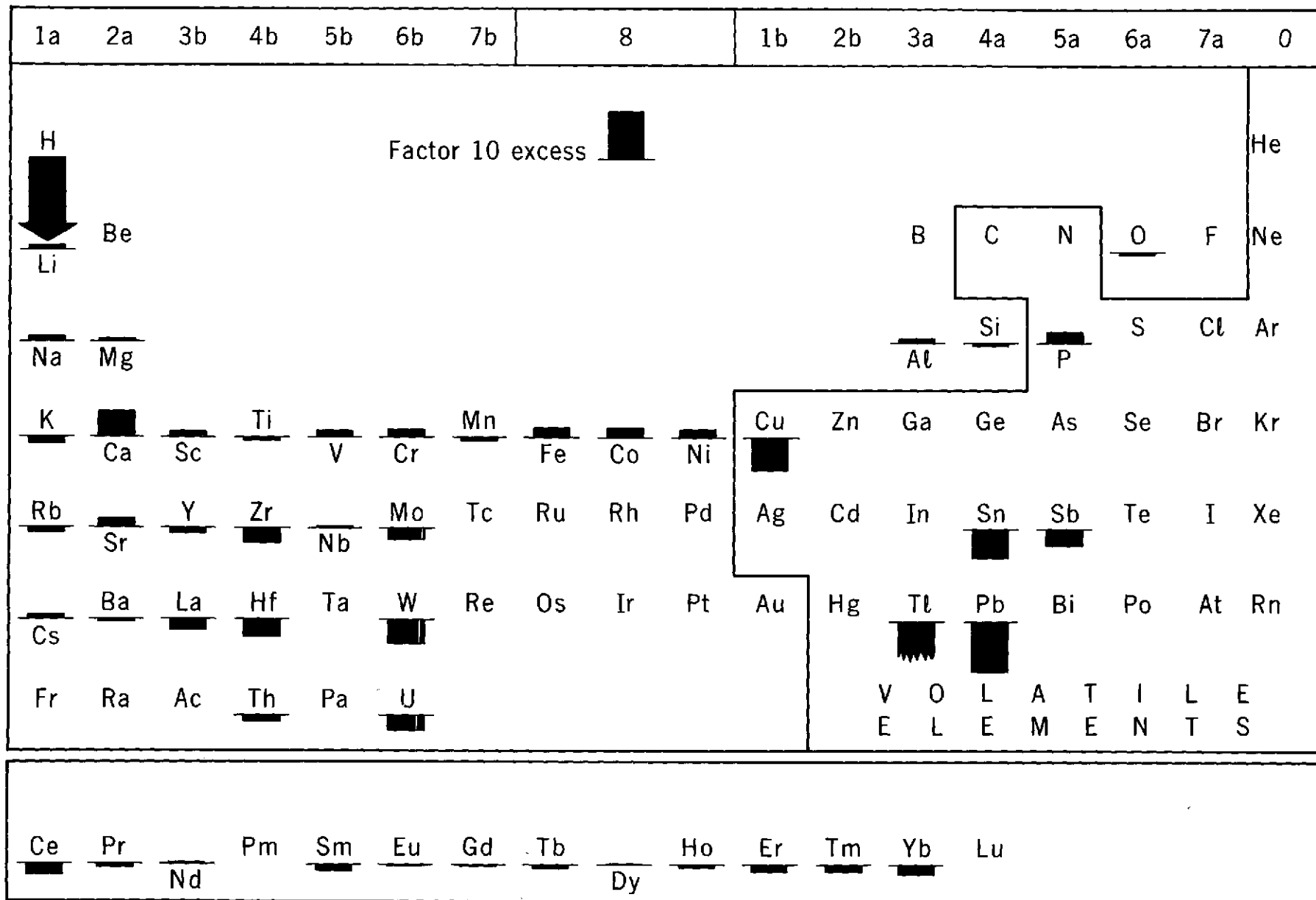


Fig. 6-4

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Fig. 6-4

EXCESS, LUNAR SAMPLE 14321, BASALTIC CLAST, OVER W-1

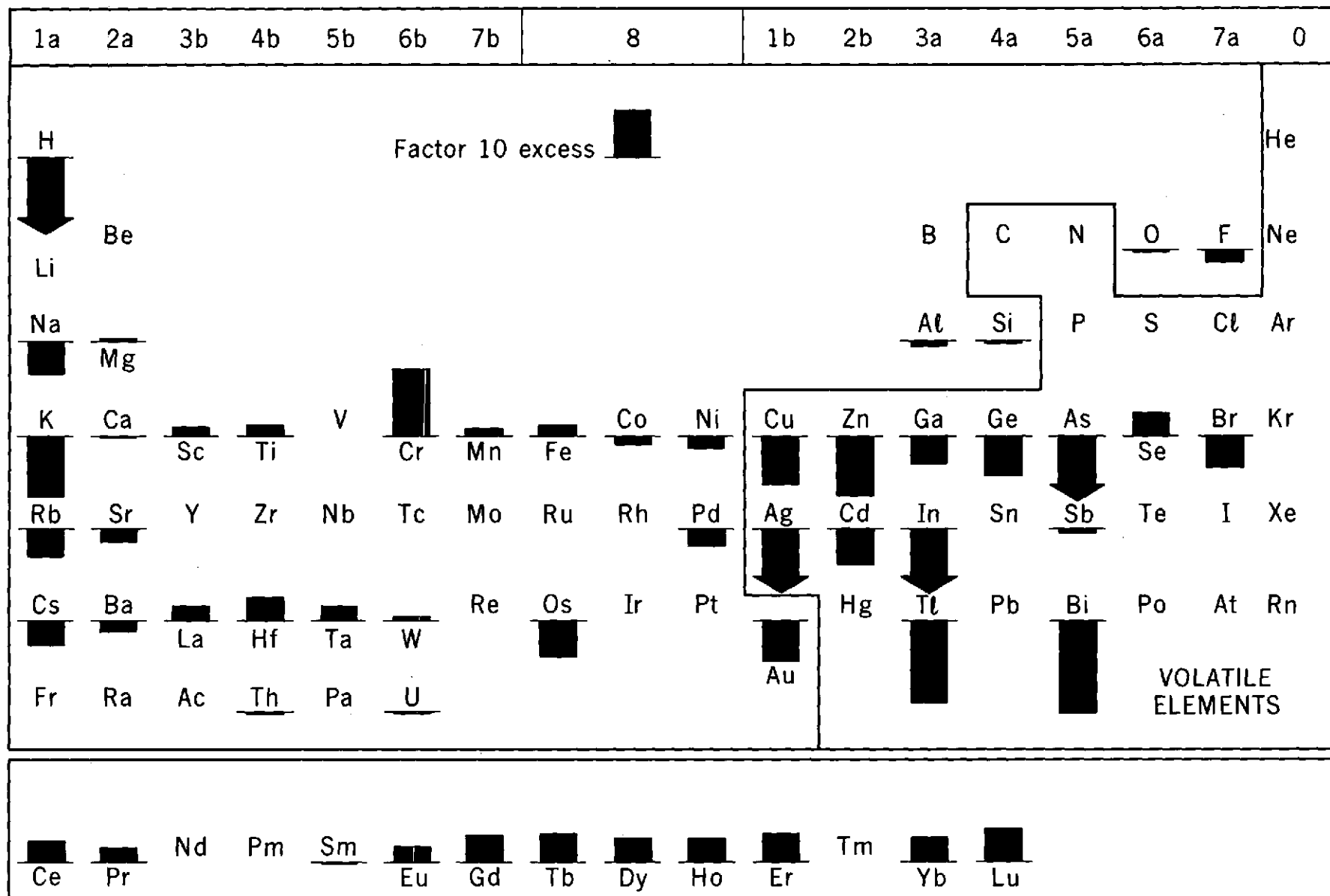


Fig. 6-5

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Fig. 6-5

EXCESS, NORMAL AUSTRALITE OVER LUNAR SAMPLE 12013

1a	2a	3b	4b	5b	6b	7b	8		1b	2b	3a	4a	5a	6a	7a	0	
H	Factor 10 excess															He	
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Tc	Mo	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ac	Th	Pa	U	V O L A T I L E E L E M E N T S												
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				

Fig. 6-6

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Fig. 6-6

Chemical Overview

The Australasian strewnfield

L Ca HAl - low calcium high aluminum

H Na/K - high sodium / potassium

H Ca - high calcium

BG -bottle-green microtektites

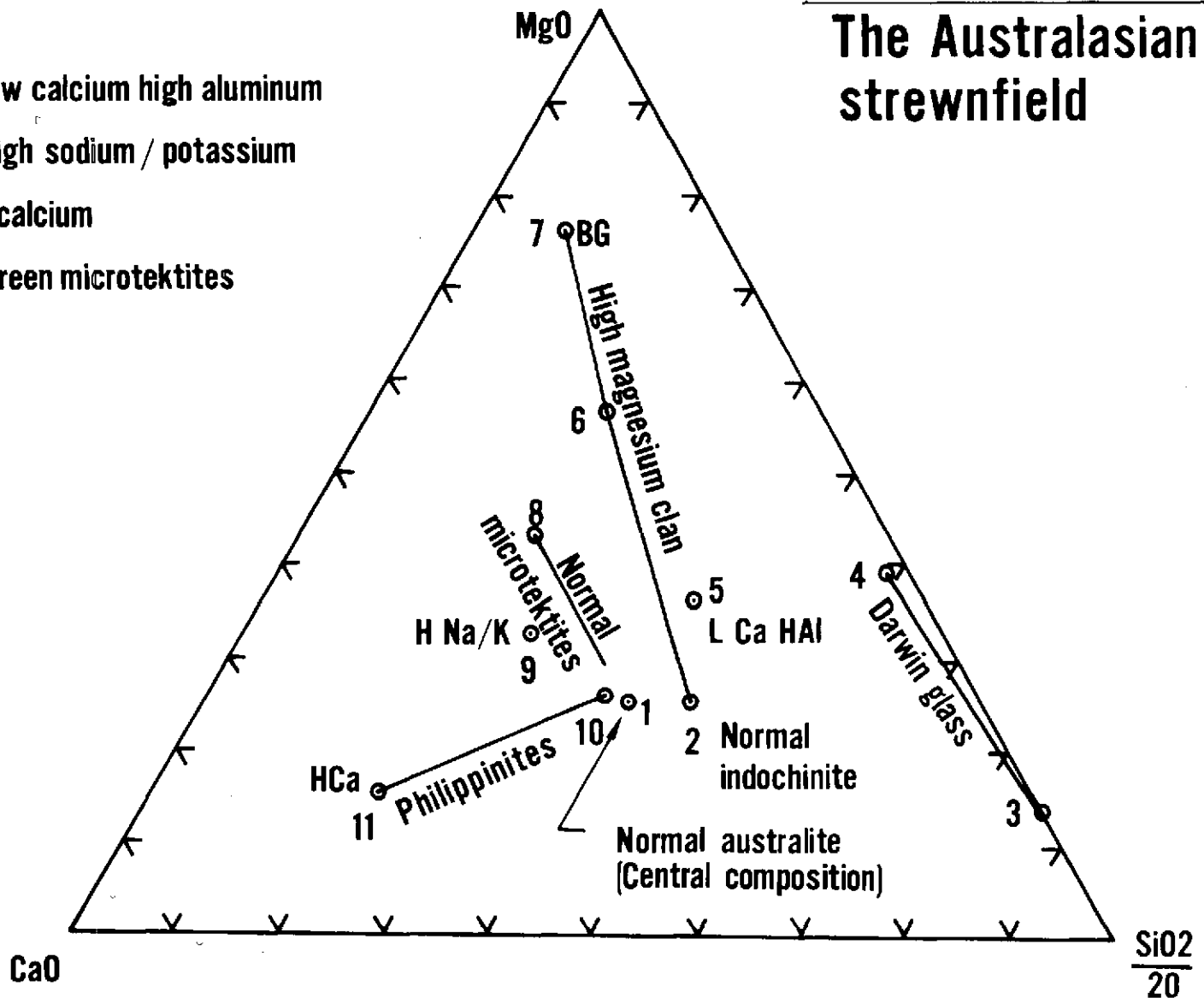


Fig. 6~7

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Fig. 6-7

Chemical Overview

Strewn Fields Other Than Australasian

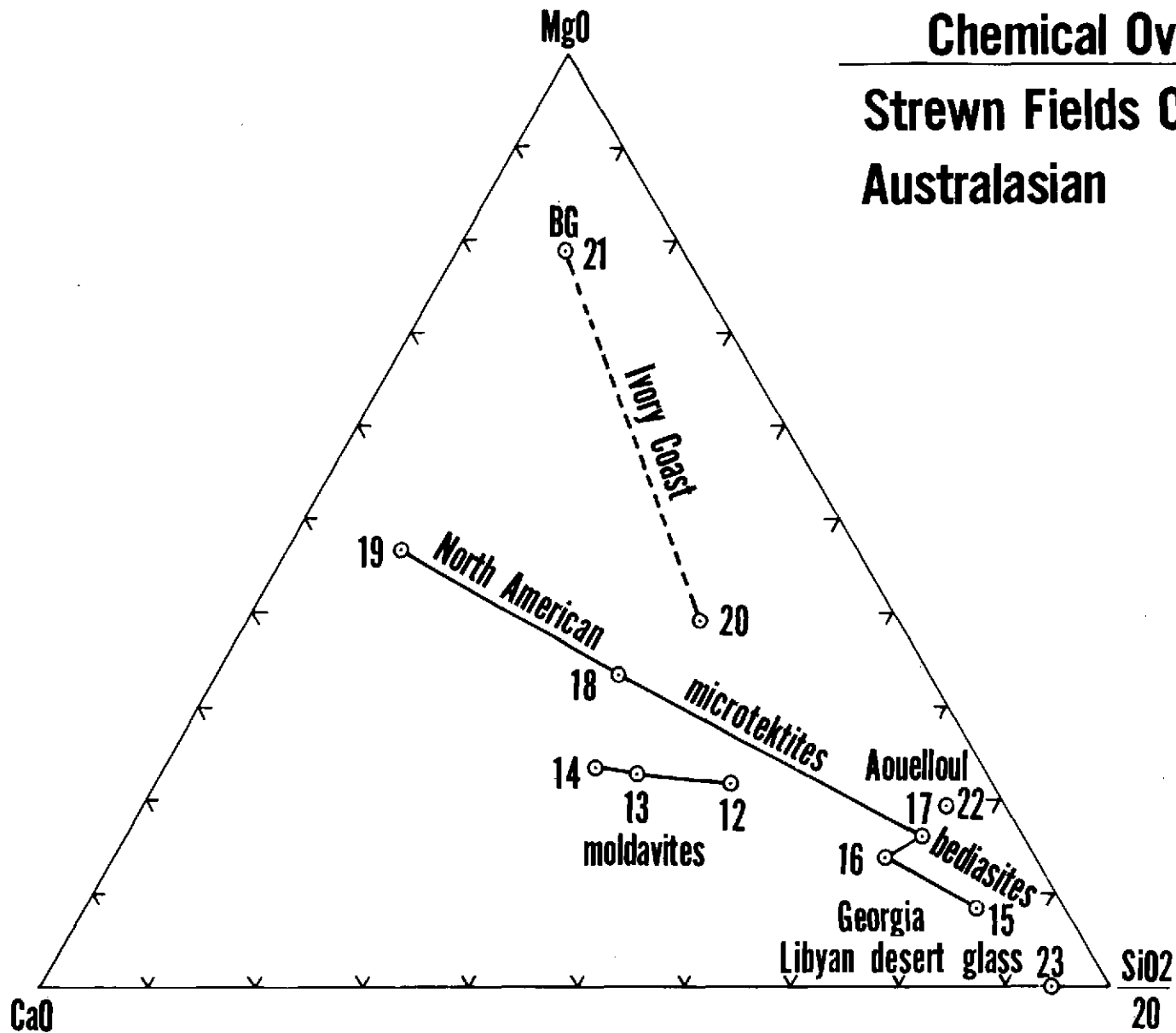


Fig. 6-8

J.A.O'Keefe

Fig. 6-8

EXCESS, IVORY COAST TEKTITES OVER BOSUMTWI GREEN AND BLACK GLASS

1a	2a	3b	4b	5b	6b	7b	8		1b	2b	3a	4a	5a	6a	7a	0		
<div><div><div>H</div><div>Factor 10 excess</div></div><div><div>Be</div><div>Li</div><div>Na</div><div>K</div><div>Cs</div><div>Fr</div></div><div><div>Ca</div><div>Mg</div><div>Sr</div><div>Rb</div><div>Ba</div><div>Ra</div></div><div><div>Ti</div><div>Sc</div><div>Y</div><div>La</div><div>Ac</div></div><div><div>V</div><div>Cr</div><div>Mn</div><div>Tc</div><div>W</div><div>Re</div><div>Os</div><div>Ir</div><div>Pt</div><div>Au</div></div><div><div>Ni</div><div>Co</div><div>Fe</div><div>Mn</div><div>Cr</div><div>V</div><div>Ti</div><div>Zr</div><div>Hf</div><div>Ta</div><div>Pa</div><div>U</div></div><div><div>Cu</div><div>Zn</div><div>Ga</div><div>Ge</div><div>As</div><div>Se</div><div>Br</div><div>Kr</div></div><div><div>Ag</div><div>Cd</div><div>In</div><div>Sn</div><div>Sb</div><div>Te</div><div>I</div><div>Xe</div></div><div><div>Au</div><div>Hg</div><div>Tl</div><div>Pb</div><div>Bi</div><div>Po</div><div>At</div><div>Rn</div></div><div><div>V</div><div>E</div><div>O</div><div>L</div><div>L</div><div>A</div><div>E</div><div>T</div><div>M</div><div>I</div><div>N</div><div>E</div><div>L</div><div>S</div></div></div>																He		
											B	C	N	O	F	Ne		
											Al	Si	P	S	Cl	Ar		
											Cu	Zn	Ga	Ge	As	Se	Br	Kr
											Ag	Cd	In	Sn	Sb	Te	I	Xe
											Au	Hg	Tl	Pb	Bi	Po	At	Rn

Fig. 6-9

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Fig. 6-9

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Fig. 6-10

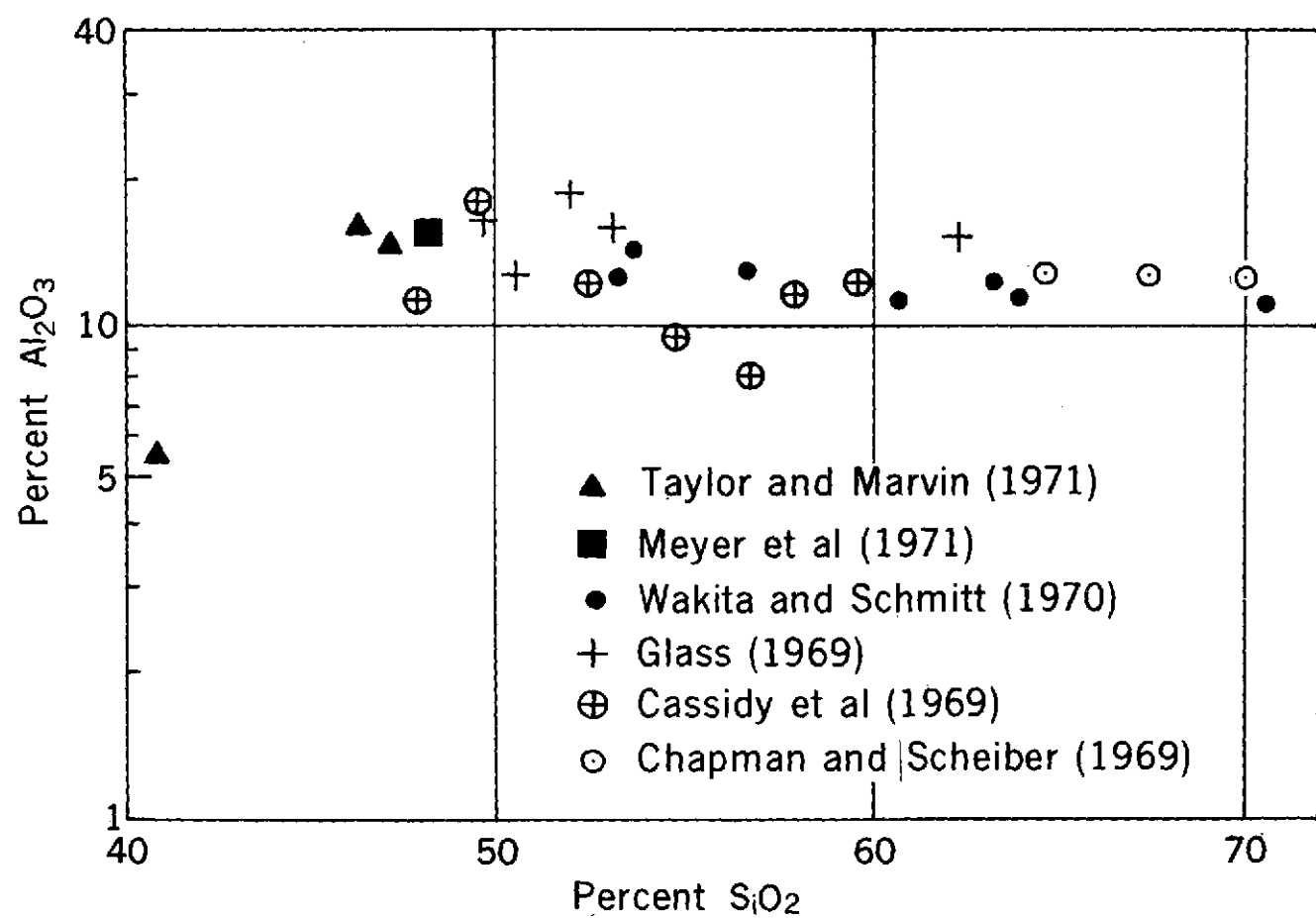
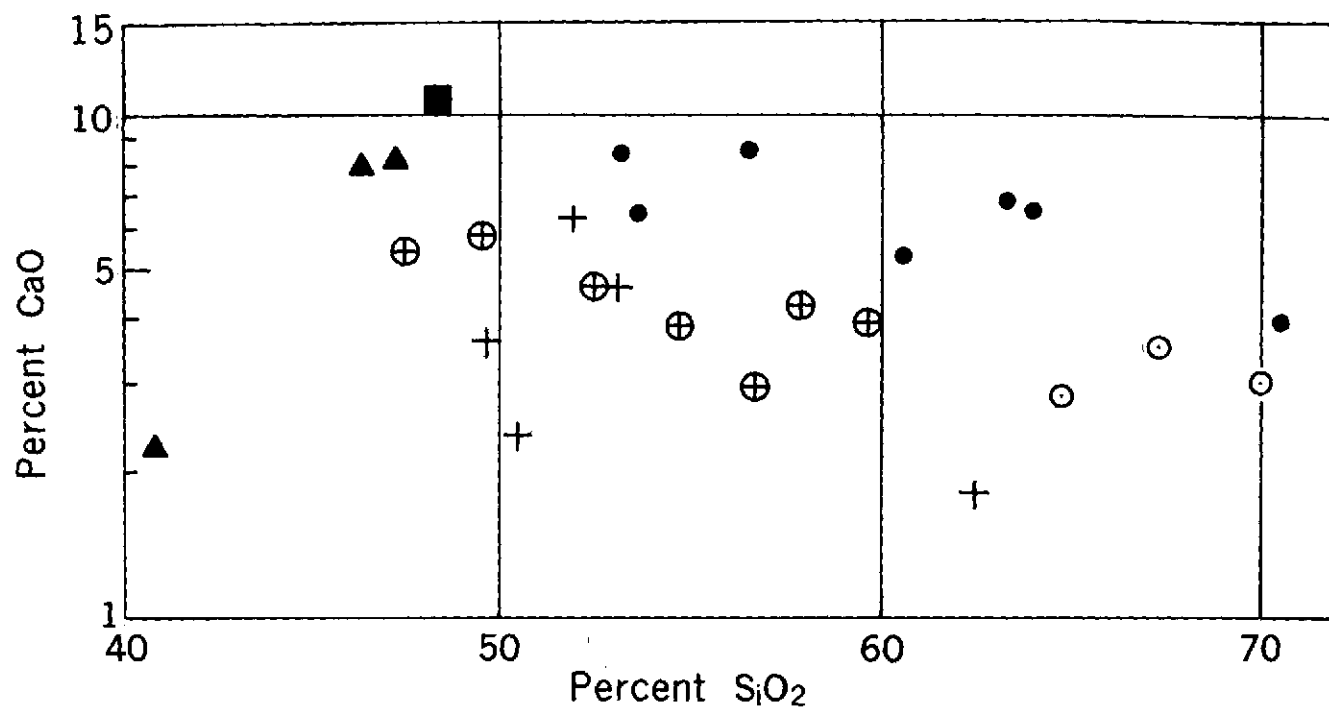


Fig. 6-11

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Fig. 6-11

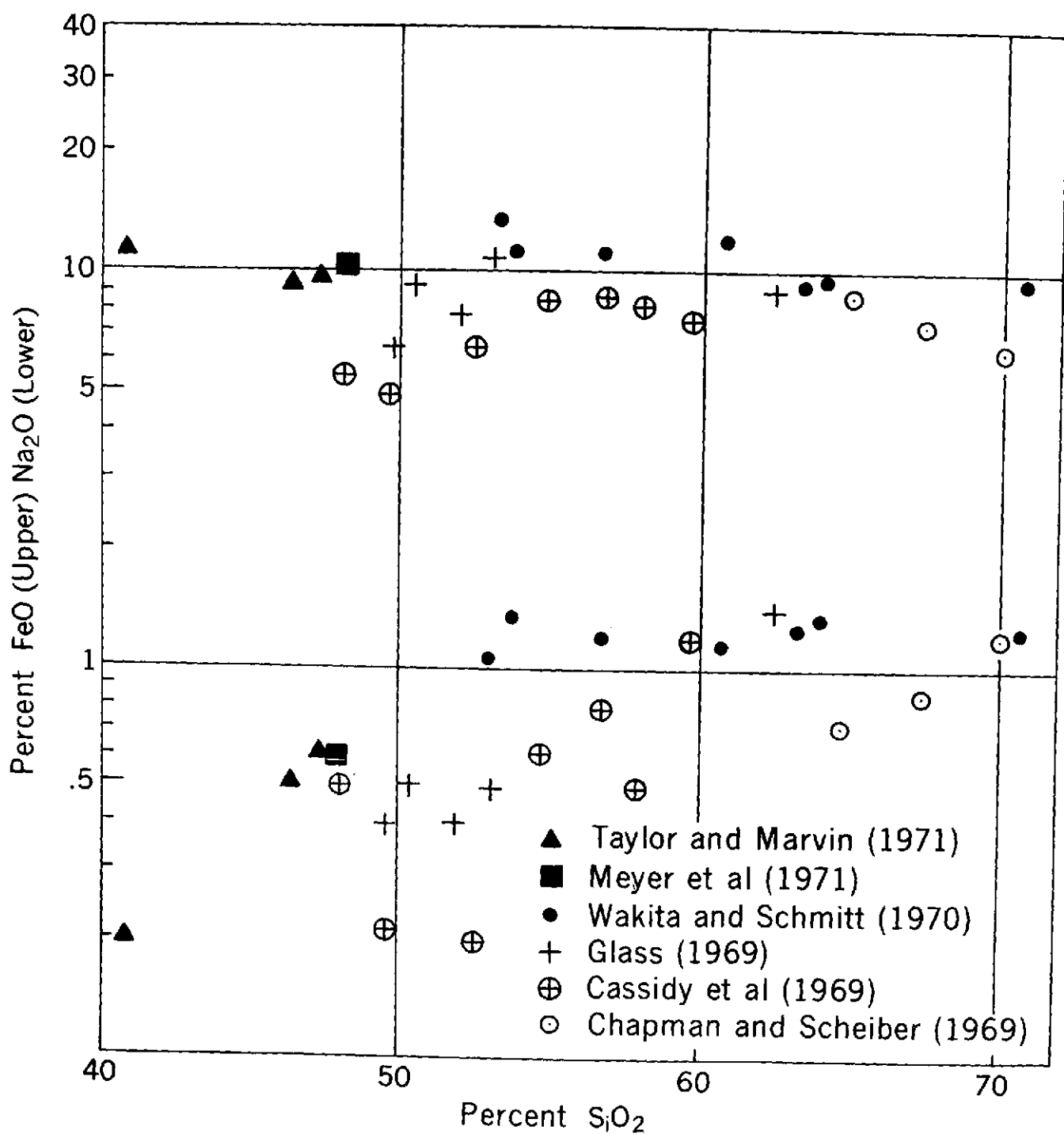


Fig. 6-12

JAO Keefe

6-12

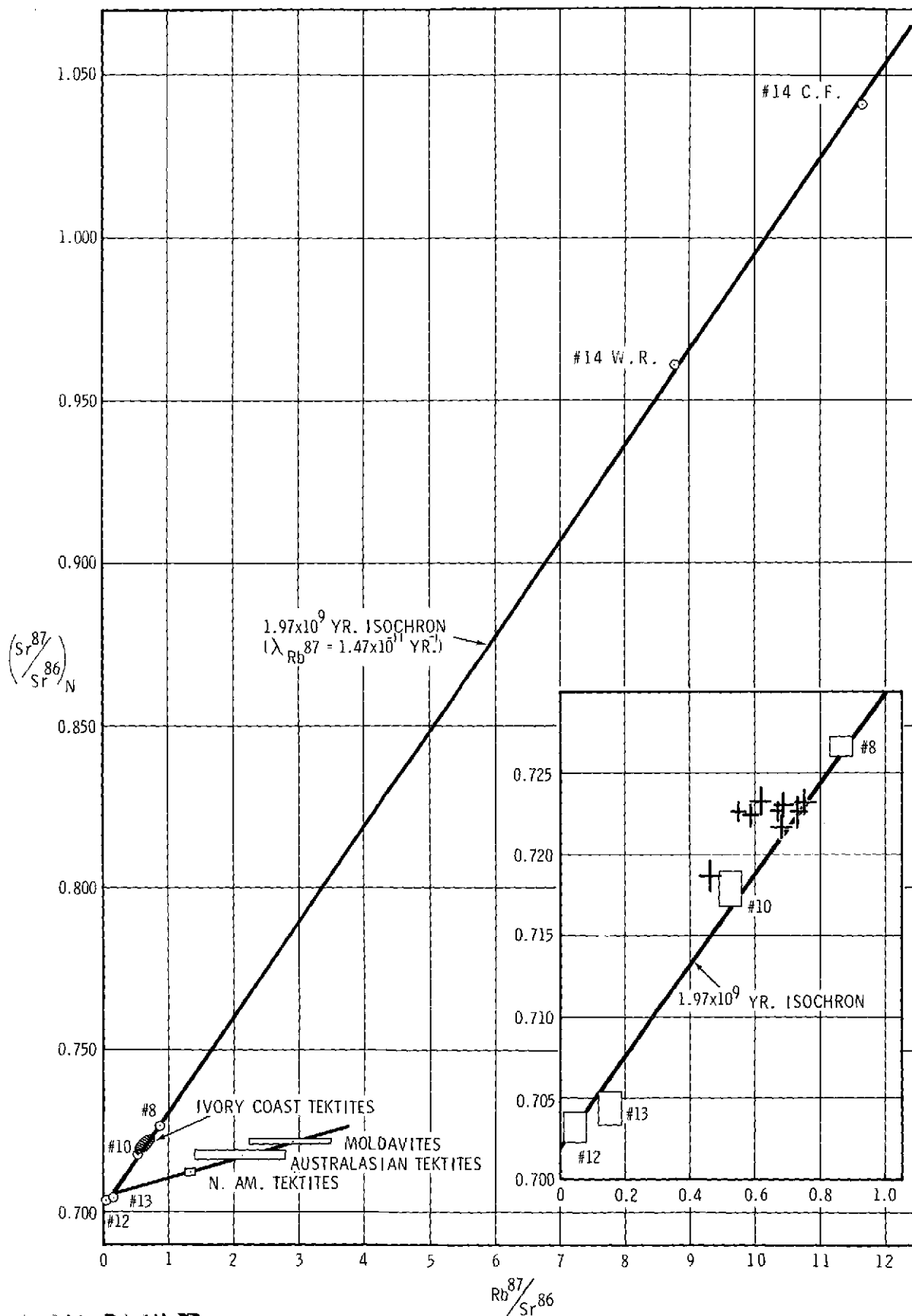


Fig. 7-1

J.A.O'Keefe

Fig. 7-1

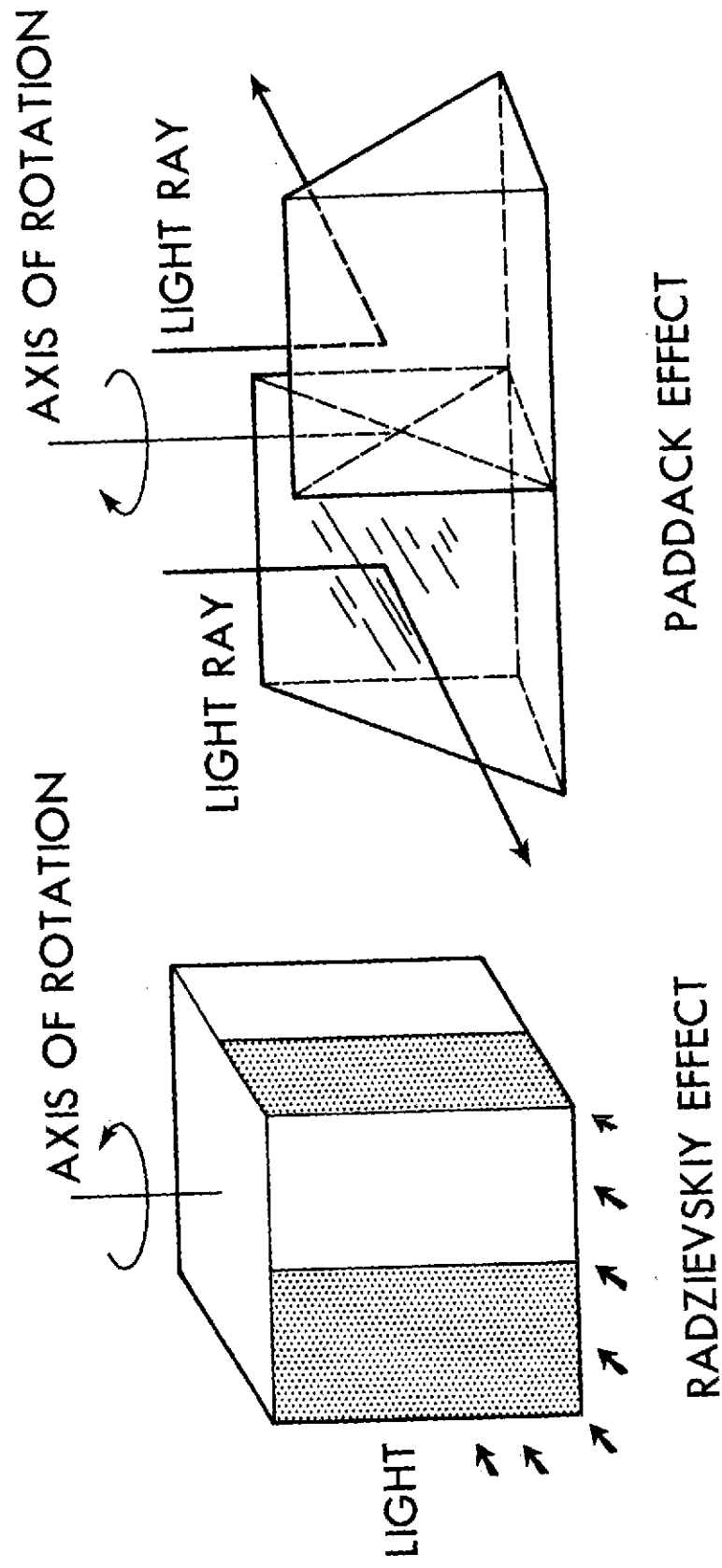


Fig. 8-1

J.A.O'Keefe

Fig. 8-1

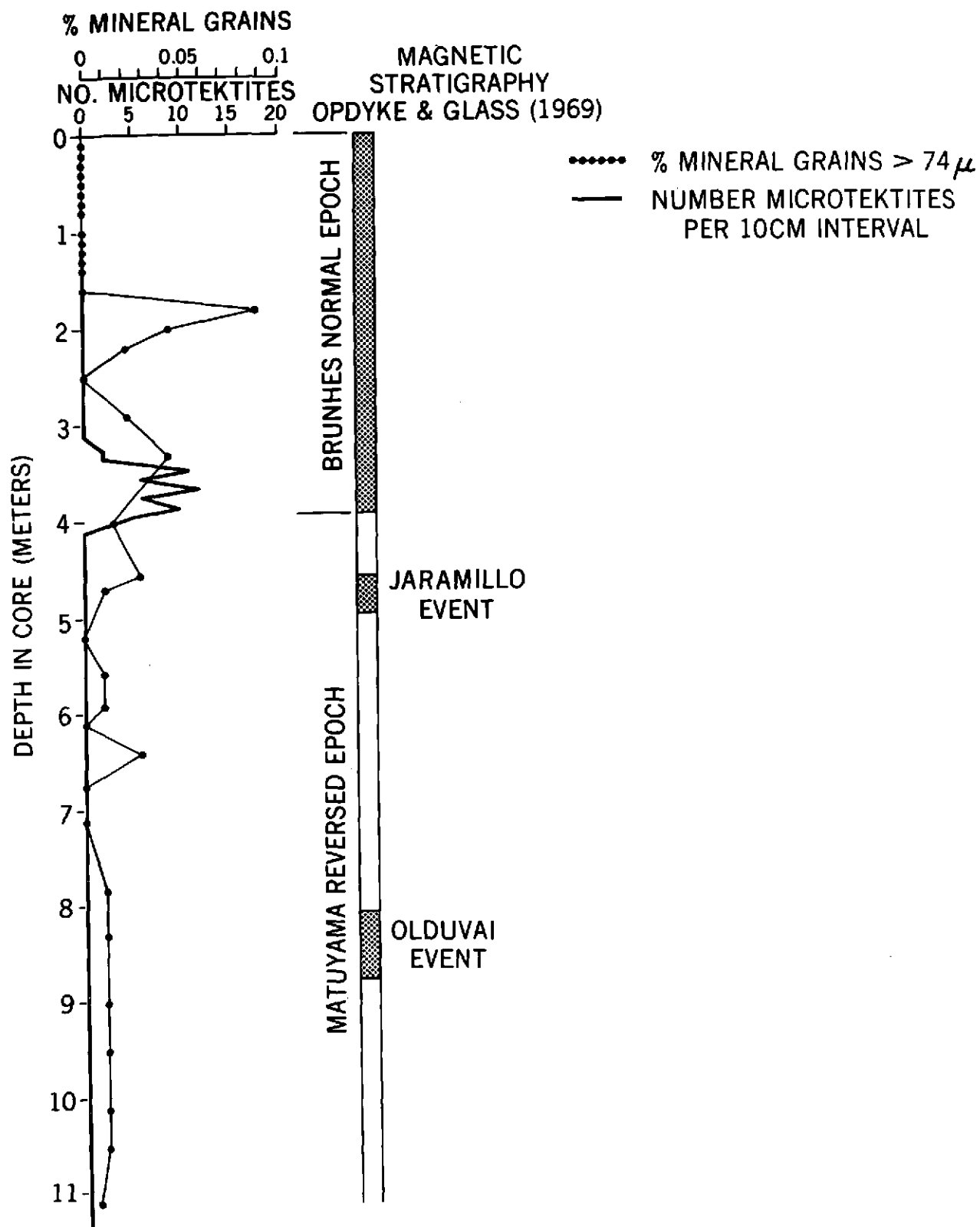


Fig. 9-1

J.A. O'Keefe

Fig. 9-1

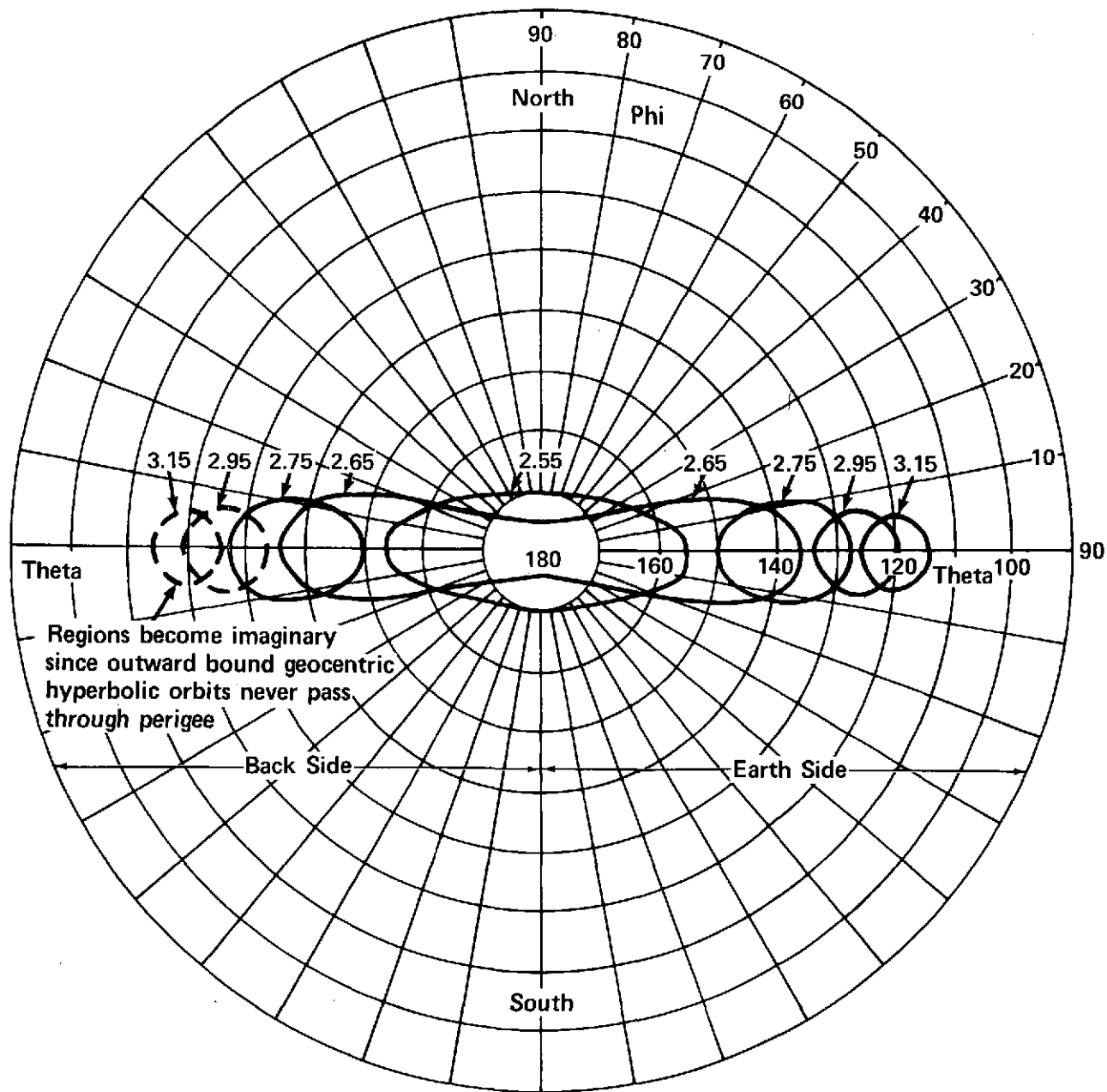
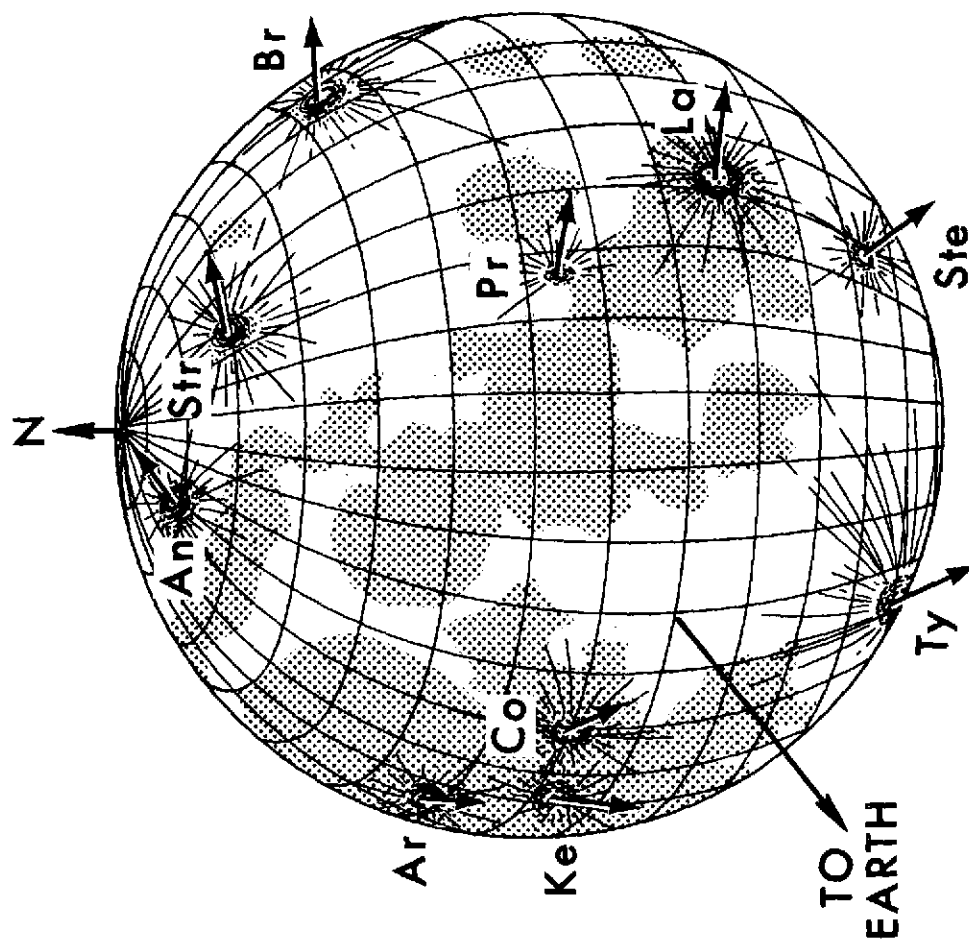


Figure 7. Velocity Strike Zones

J.A.O'Keefe

Fig. 10-1



- An ANAXAGORAS
- Ar ARISTARCHUS
- Br BRUNO
- Co COPERNICUS
- Ke KEPLER
- La LANGRENUS
- Pr PROCLUS
- Ste STEVINUS
- Str STRABO
- Ty TYCHO

Fig. 10-2

J.A.O'Keefe

Fig. 10-2

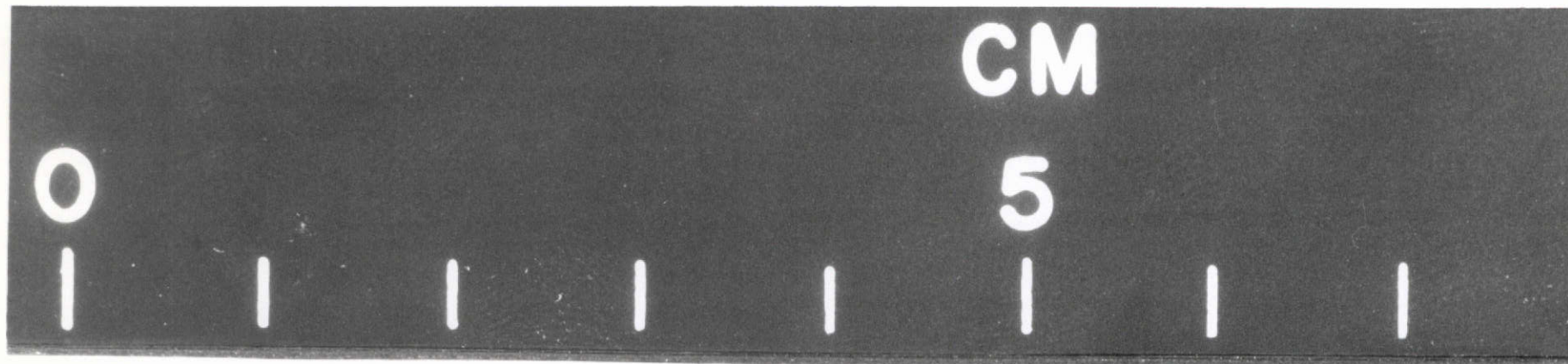


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2-1
J.A. O'Keefe

TOP

2-1
J.A. O'Keefe

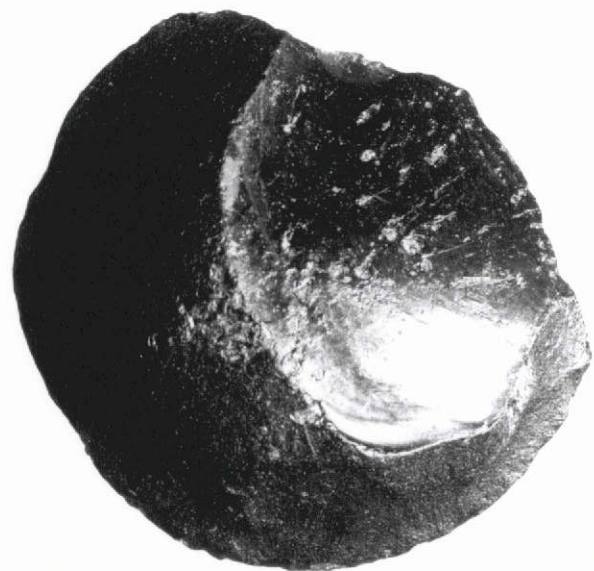
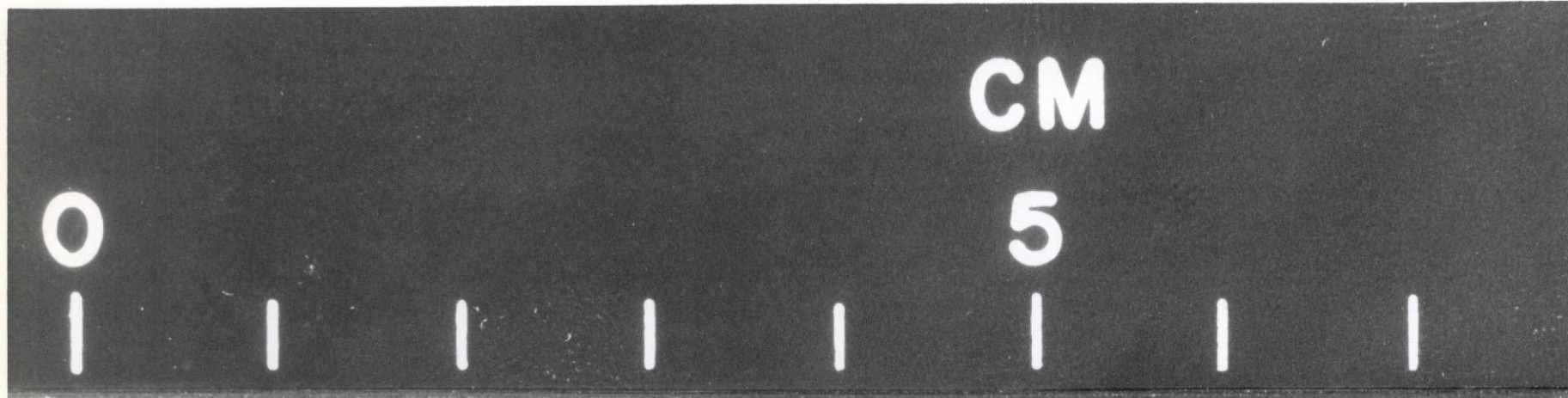


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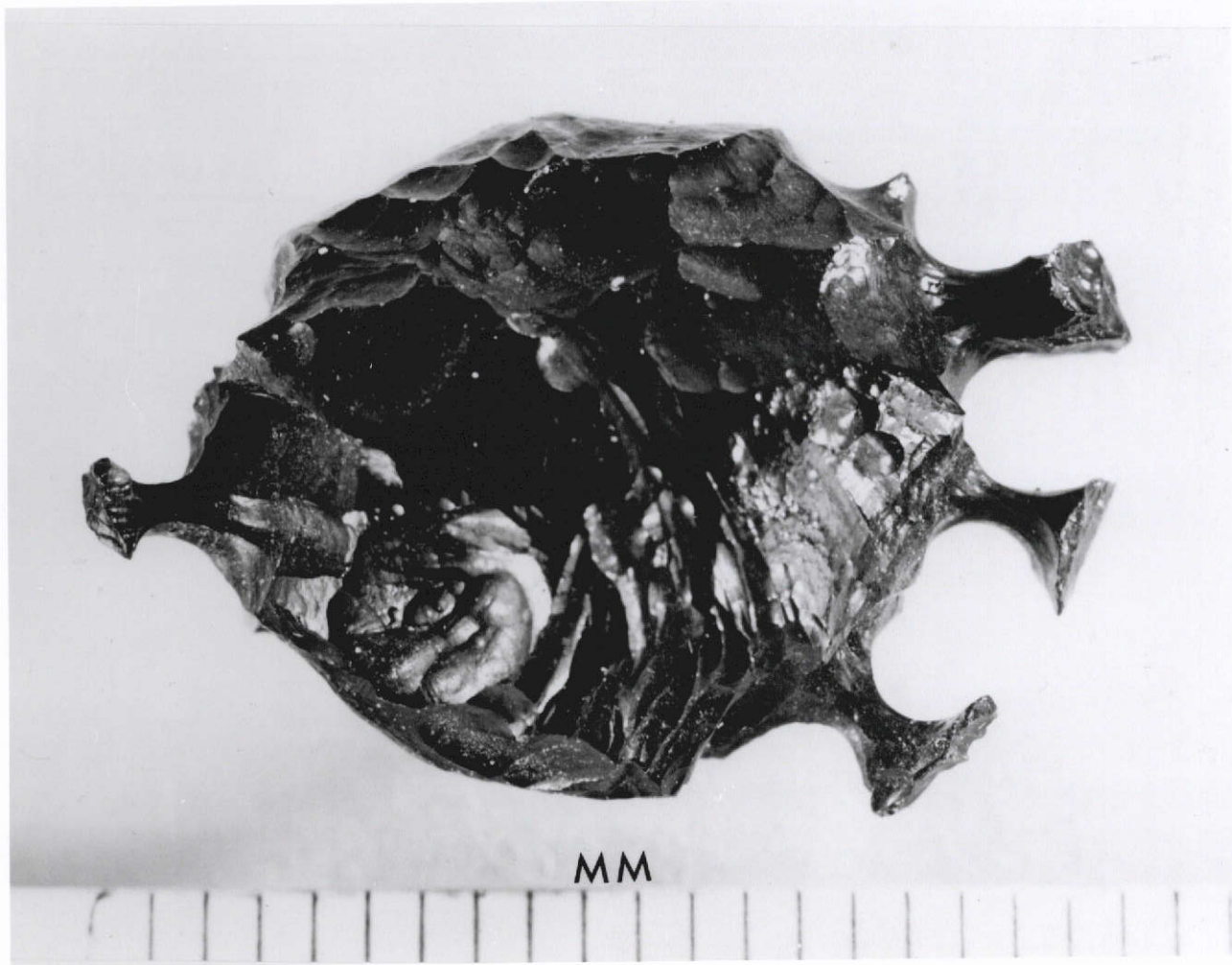
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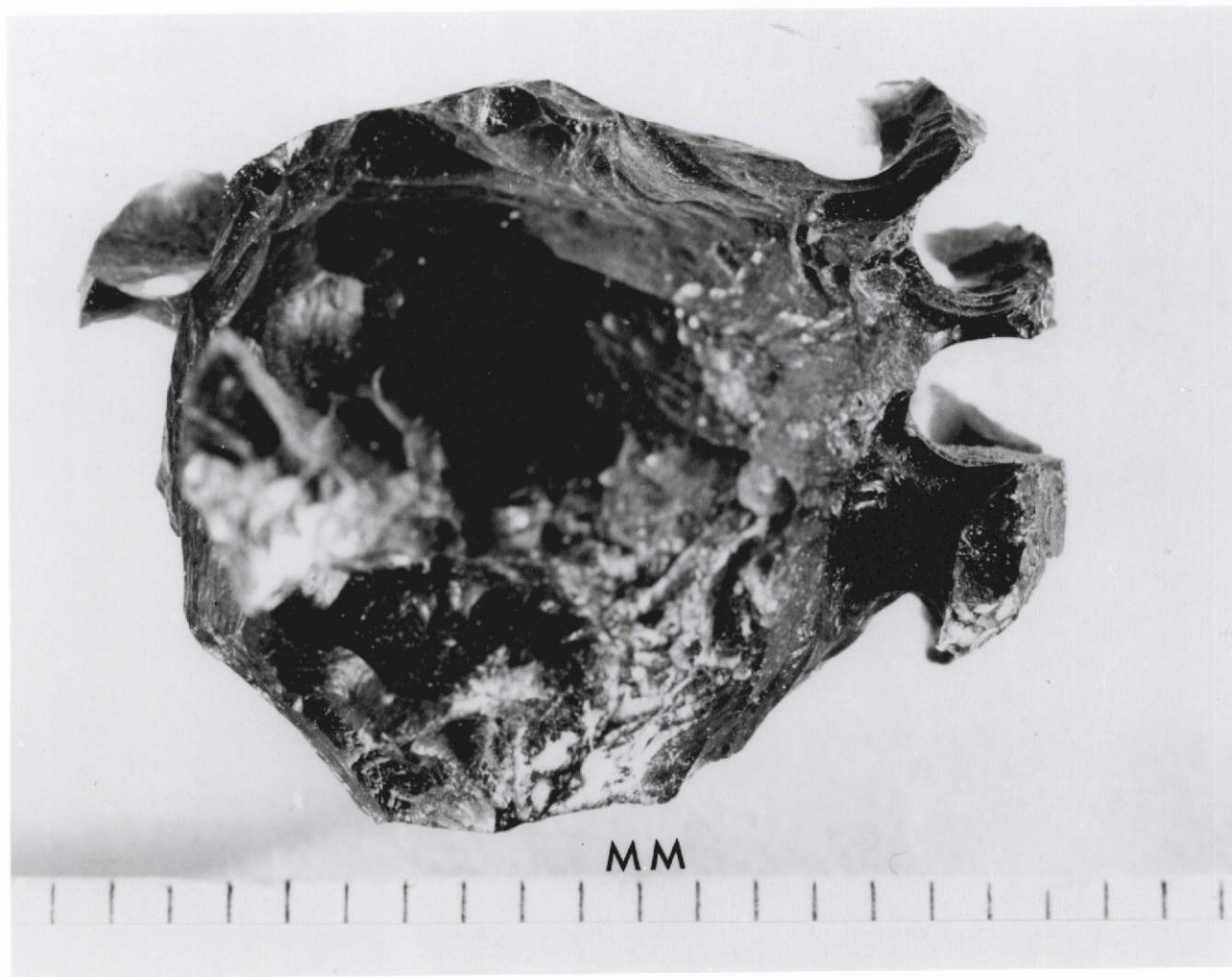
Ja. O'Keefe

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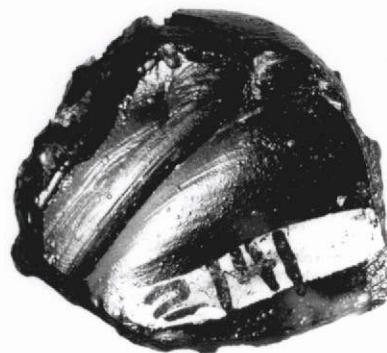
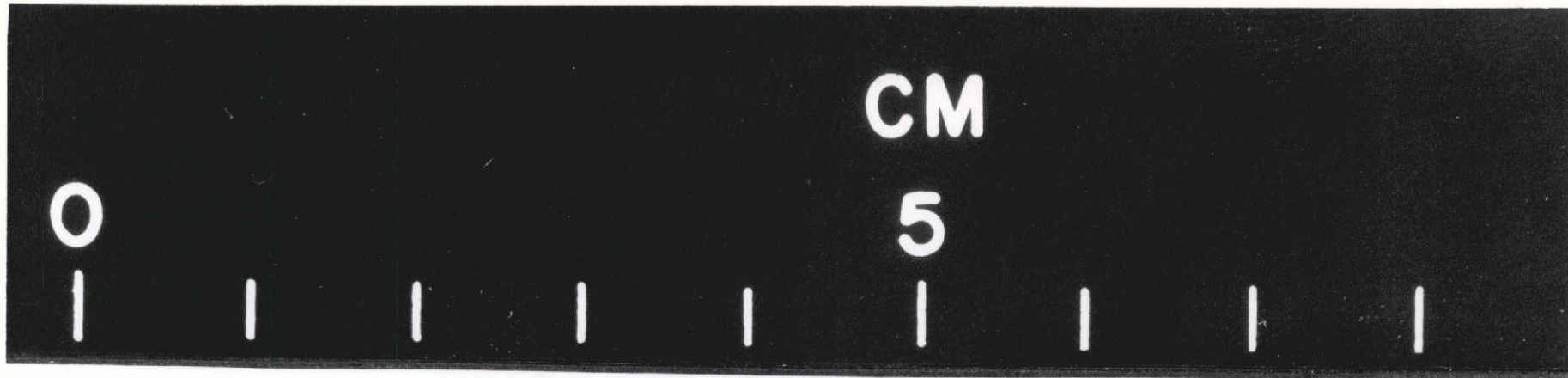
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S.A.O. Kupa

2-4 S.A.O. Kupa top



i-5

J. A. O'Keefe



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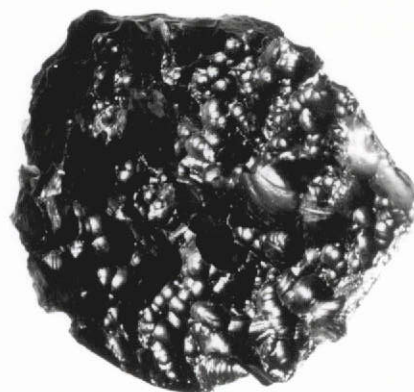
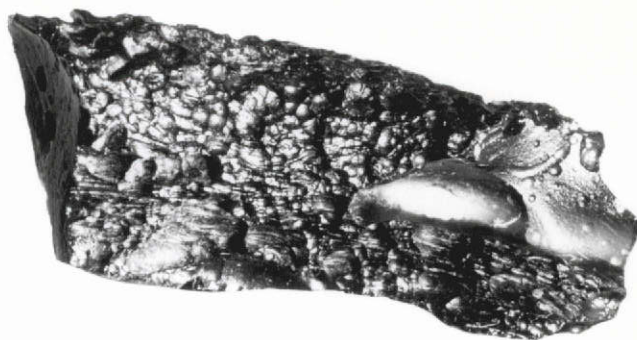
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J. A. O'Keefe

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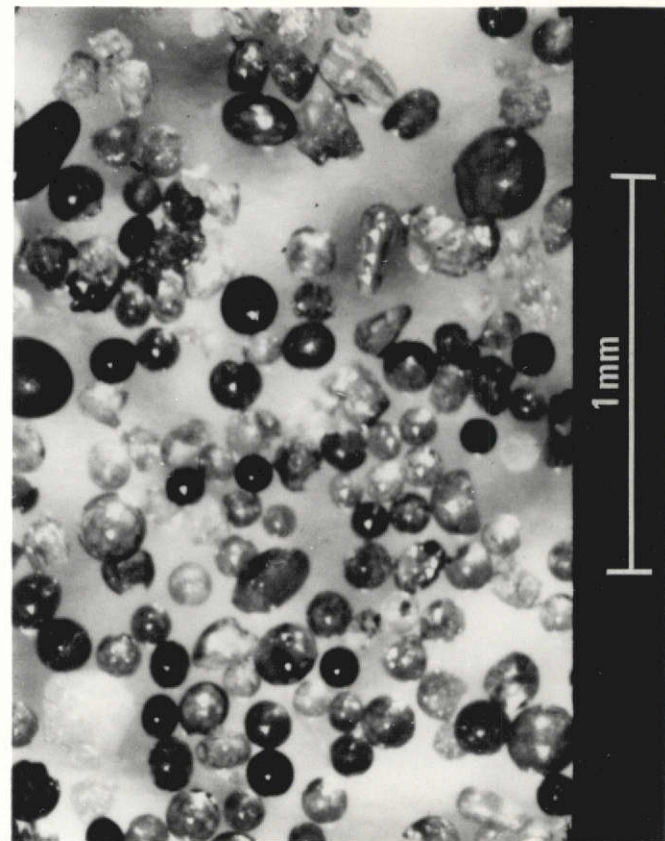
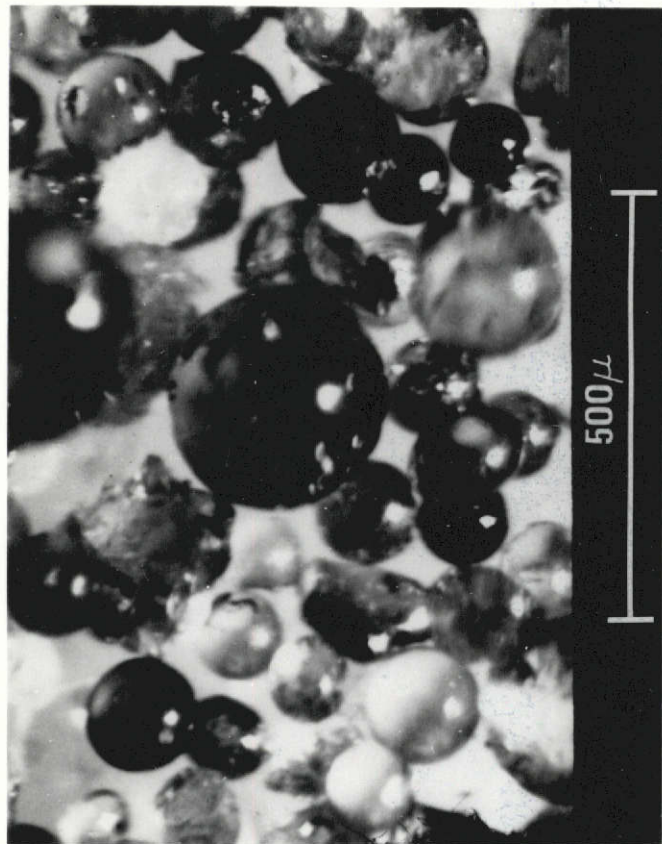
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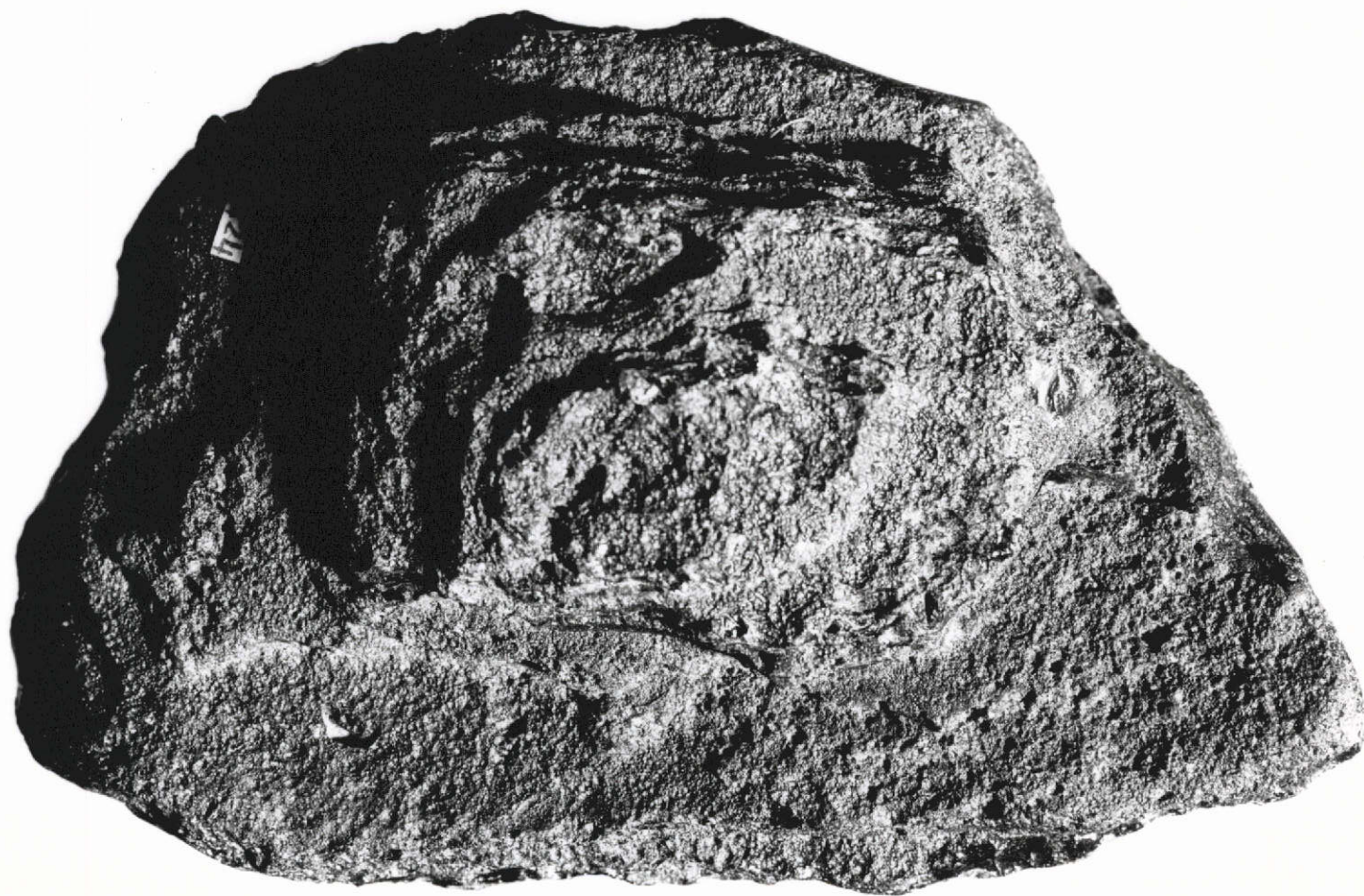
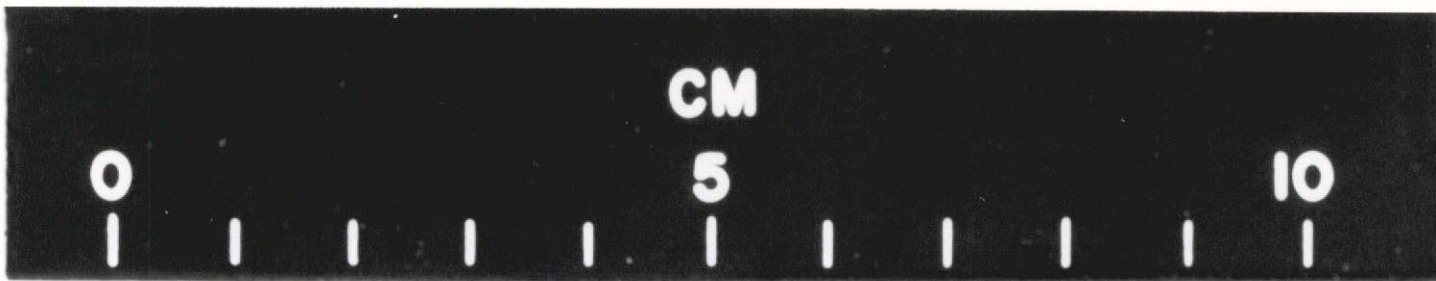
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i-7
J.A. O'Keefe



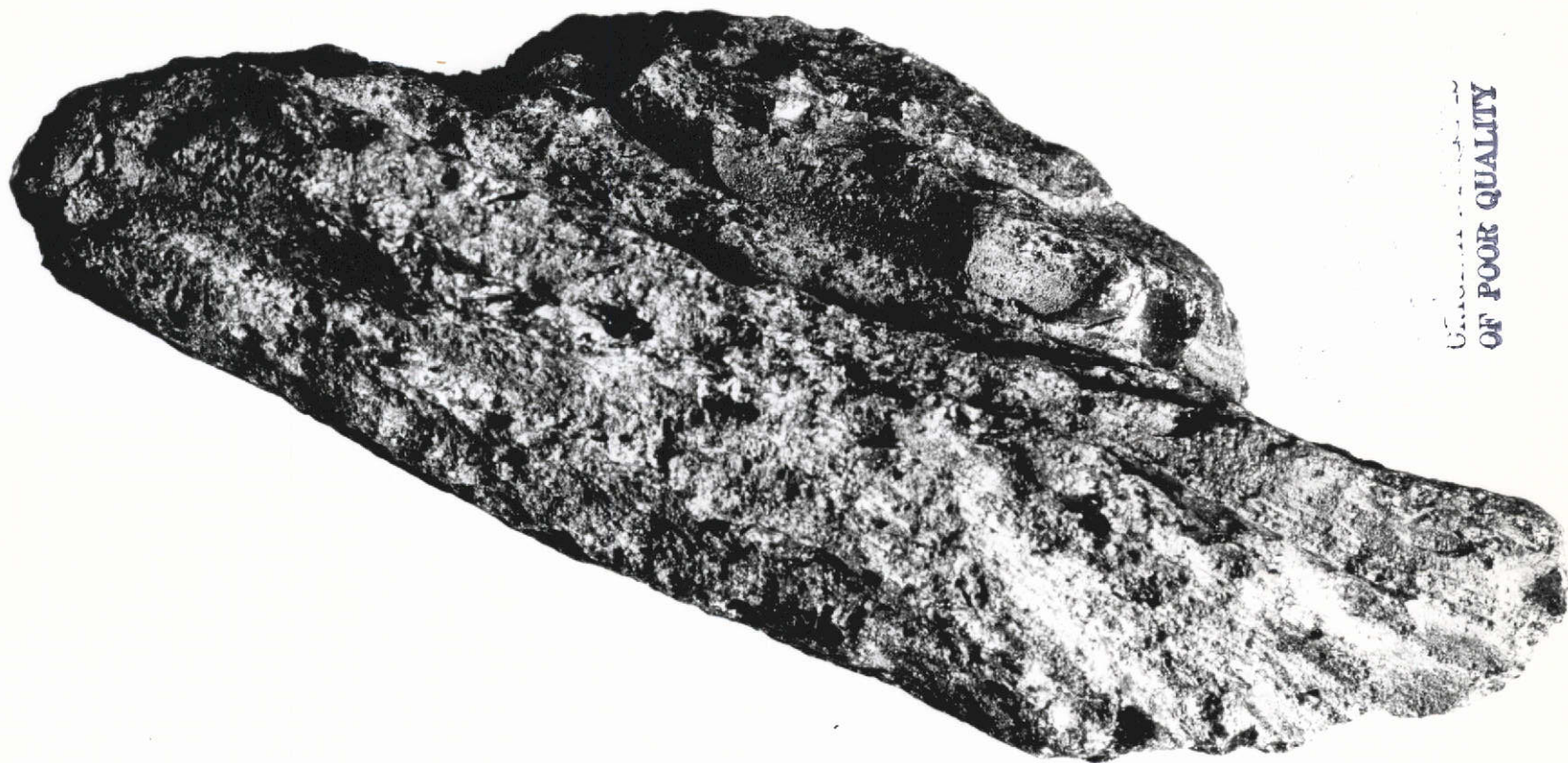
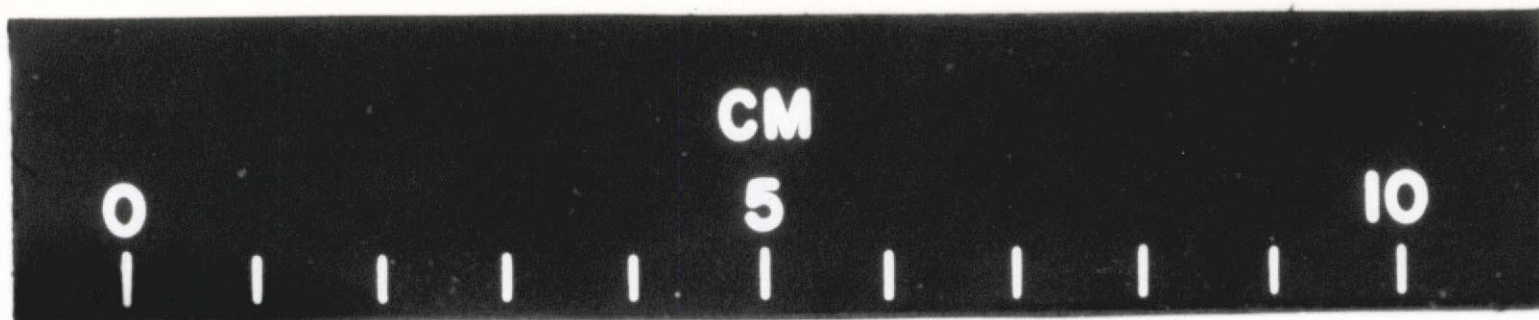
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S.A. O'Keefe



2-9
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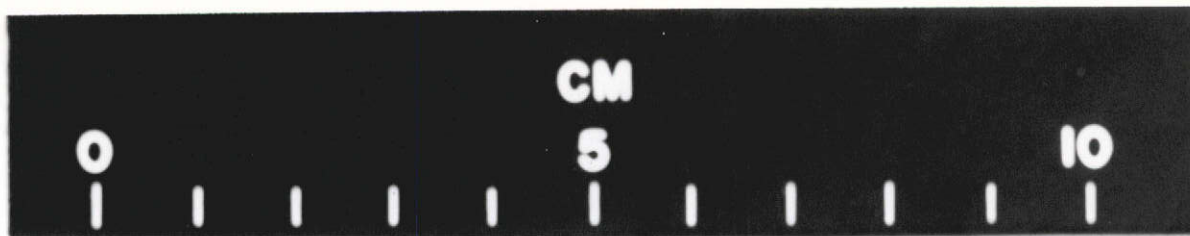
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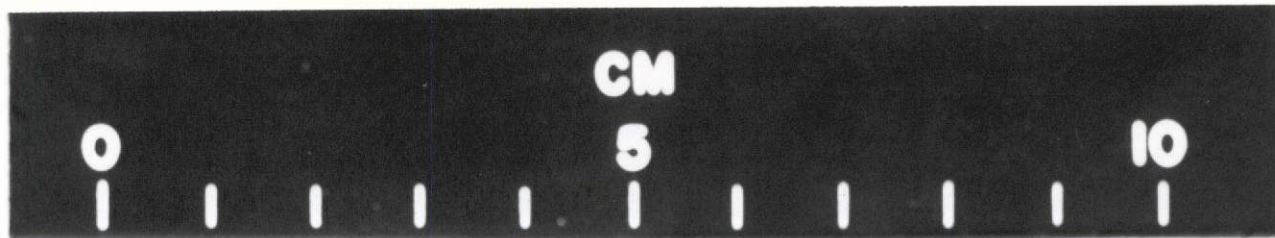
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J. A. O'Keefe



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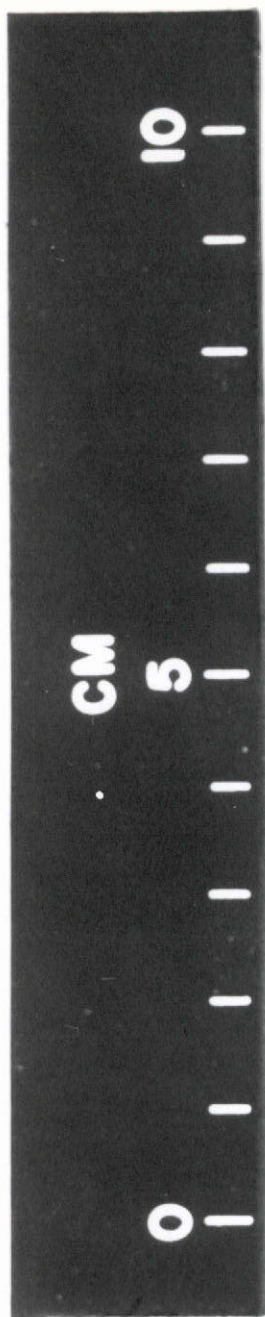
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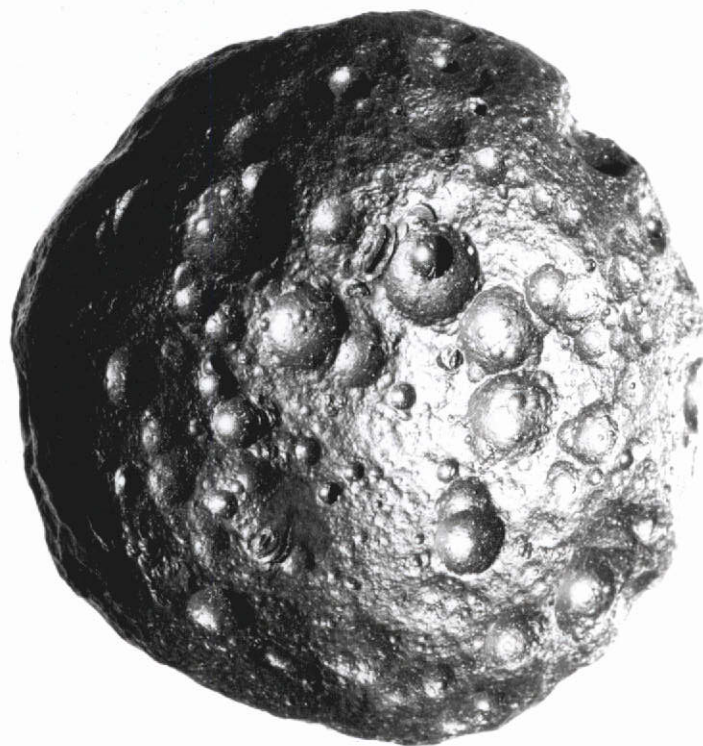
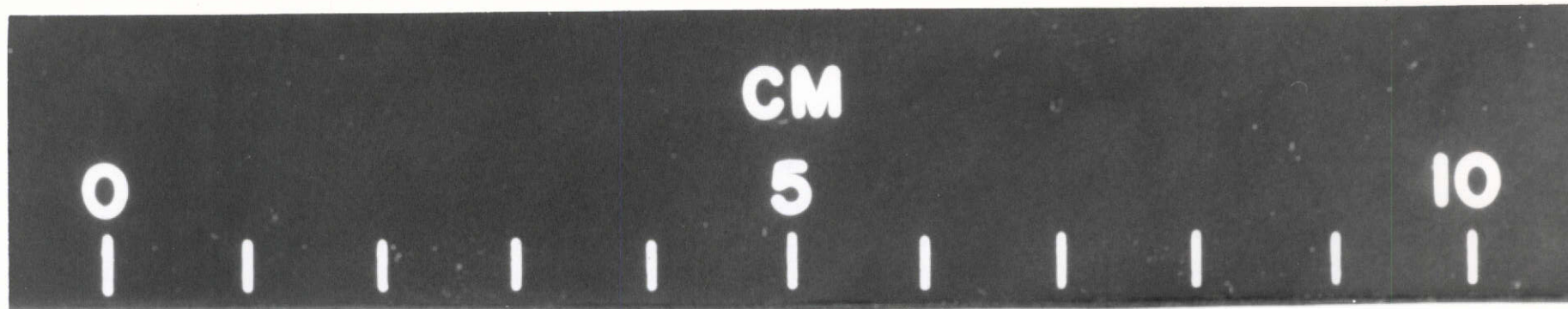
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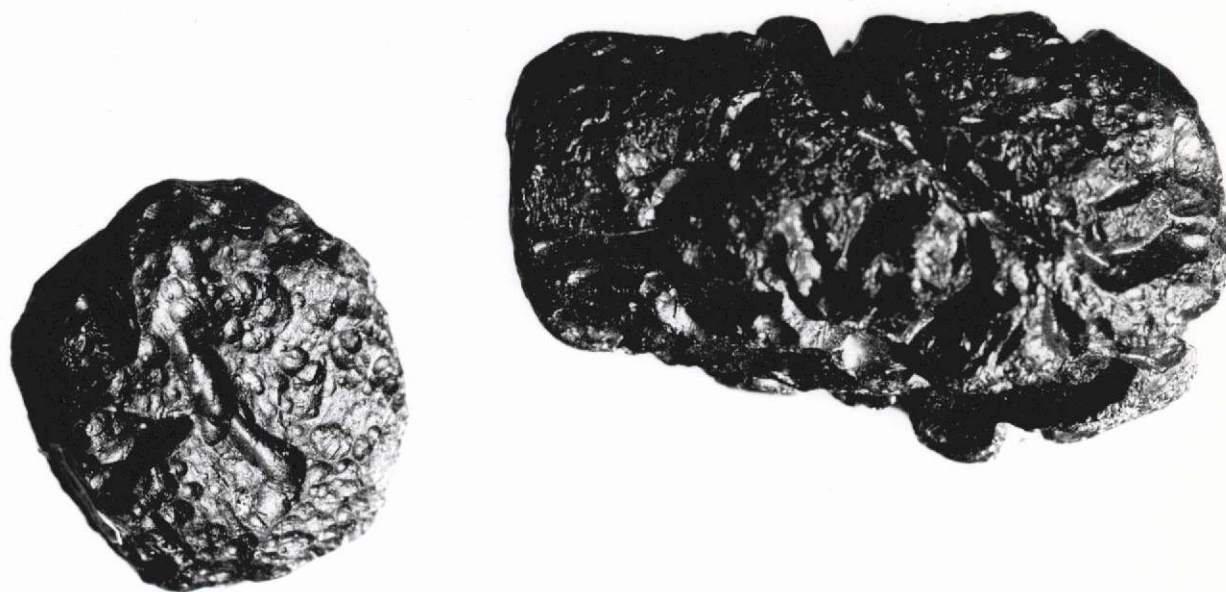
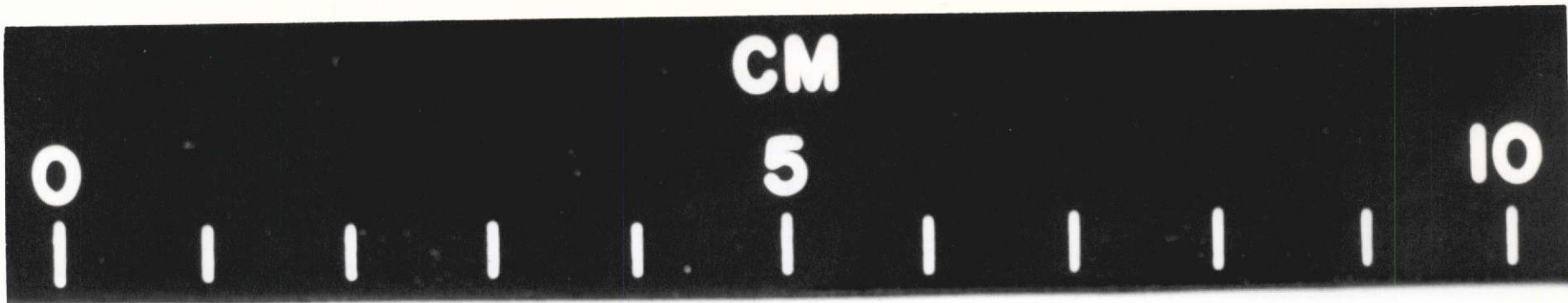


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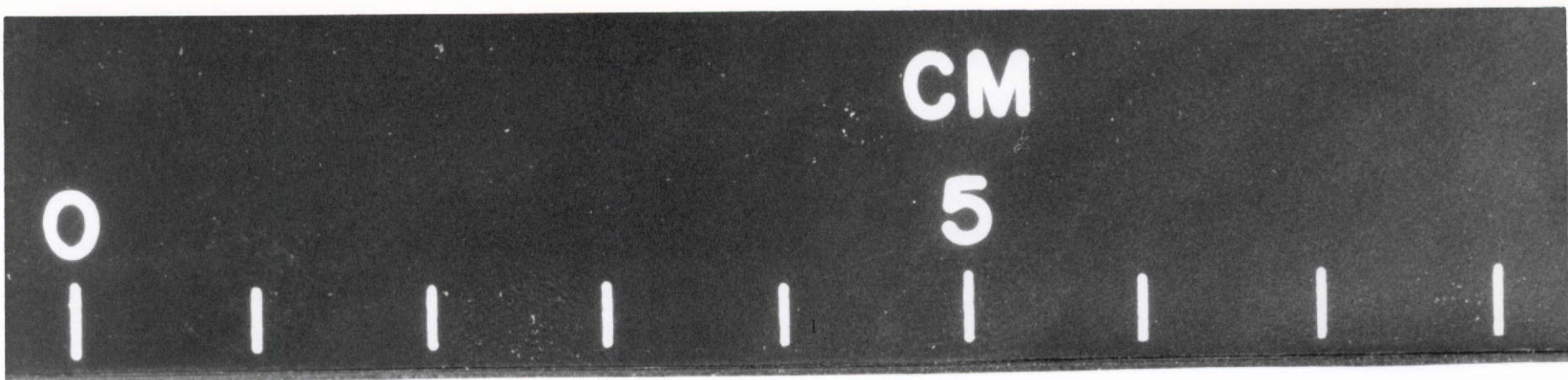


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J. A. O'Keefe



² - 15
g.a.o. Keefe



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J. A. O'Keefe

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J.A.O. Kiefer

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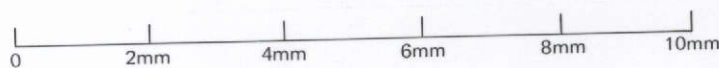
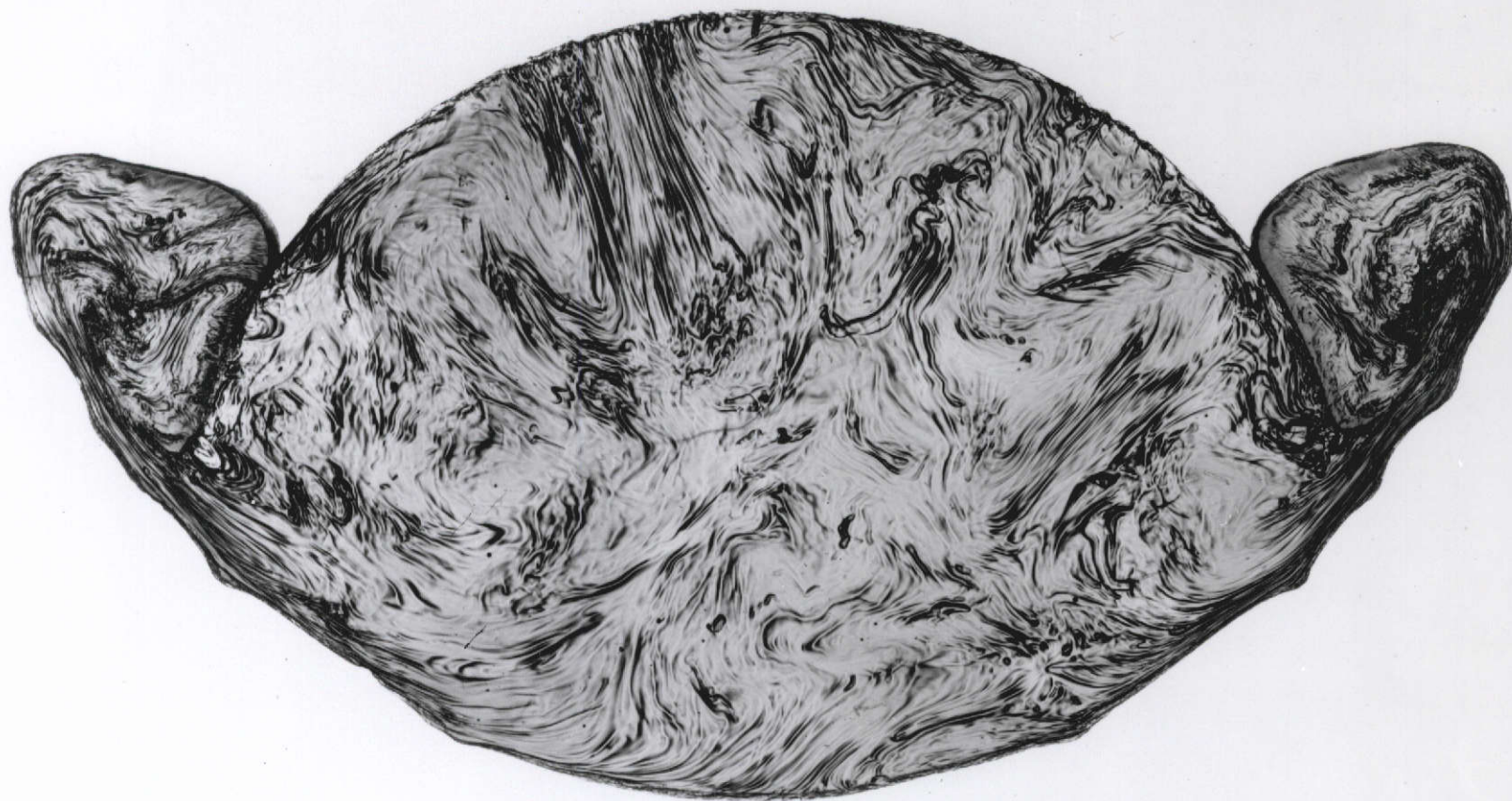


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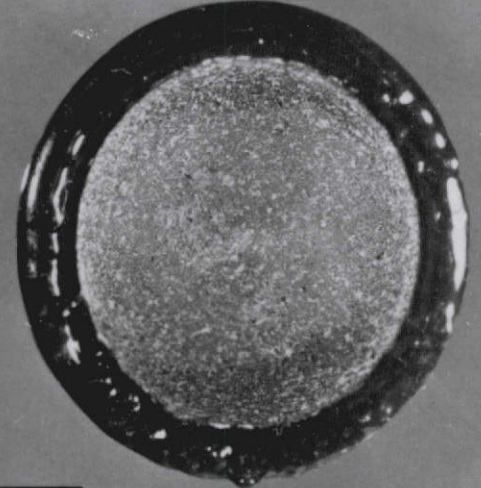
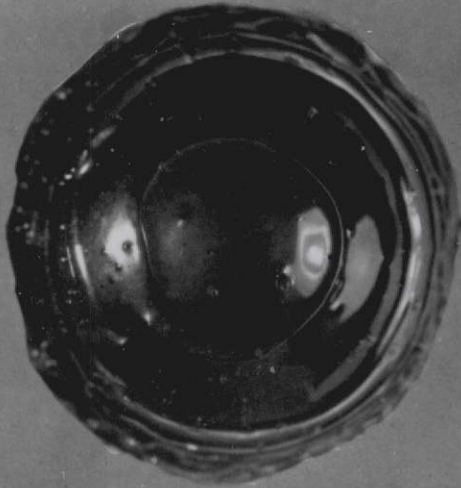
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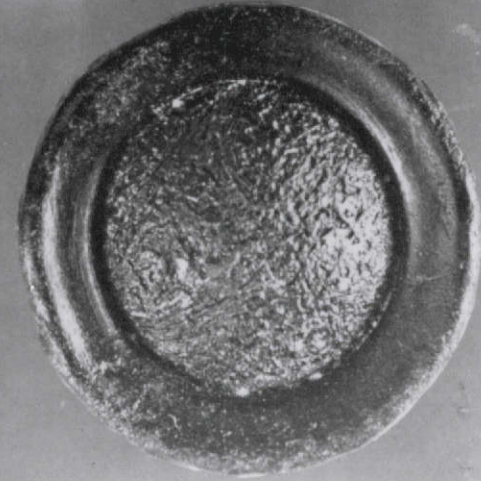
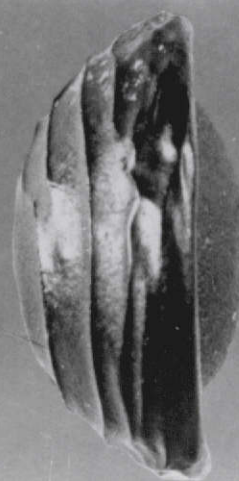
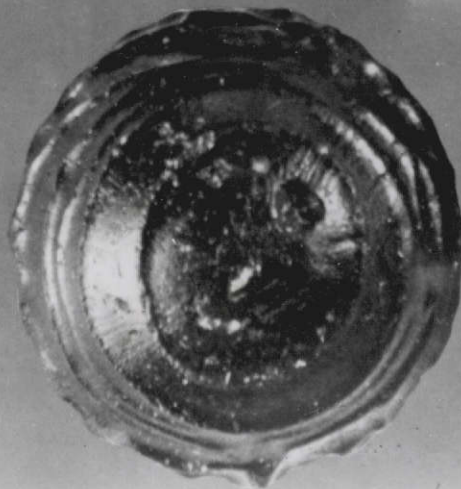
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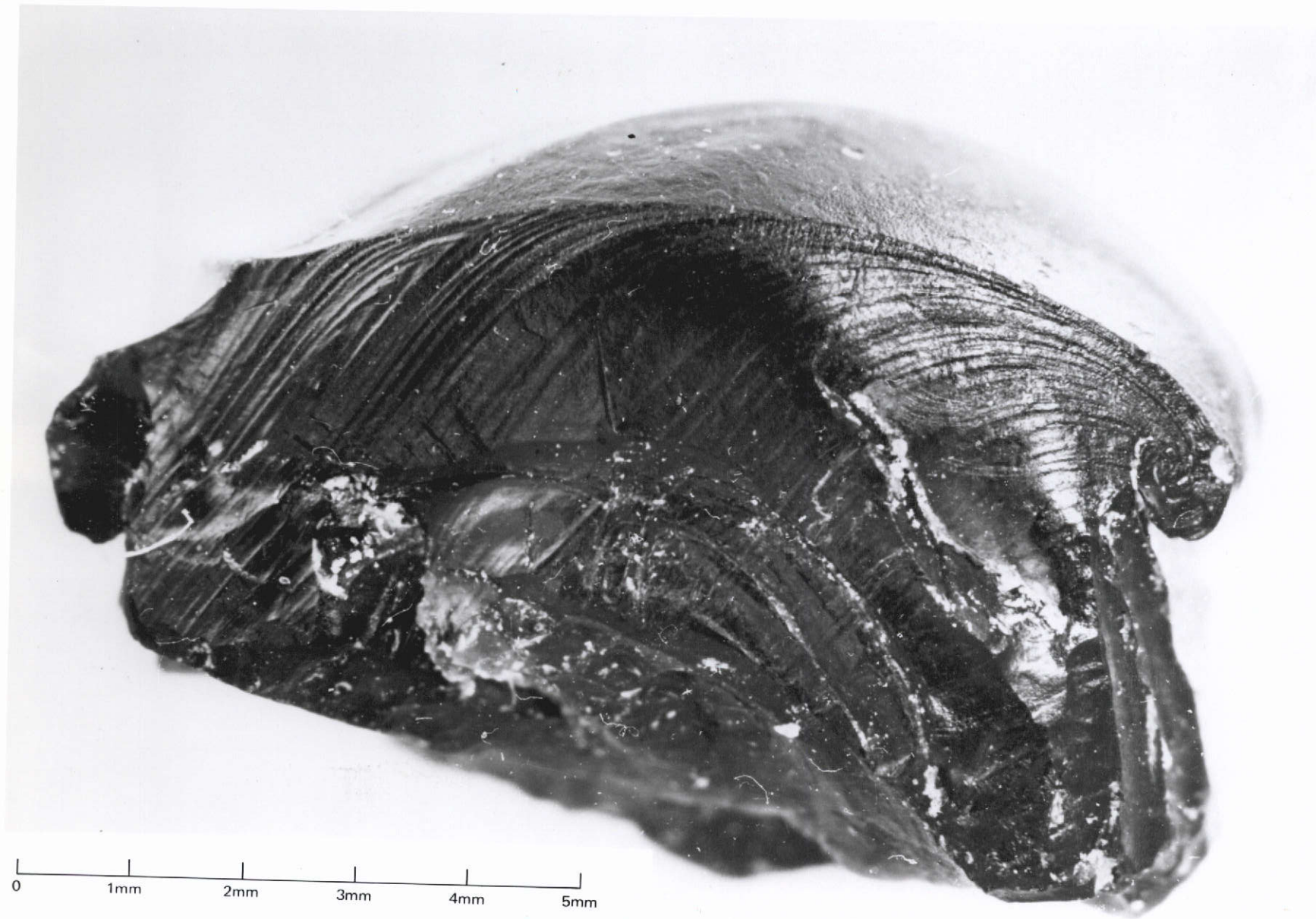
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AERODYNAMIC ABLATION OF TEKTITE GLASS



AUSTRALIAN TEKTITES

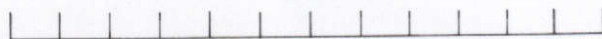




2-22 J.A. O'Keefe

AUSTRALASIAN TEKTITE CORES

cm



SOUTHEAST AUSTRALIA (VICTORIA)



SOUTHWEST WESTERN AUSTRALIA

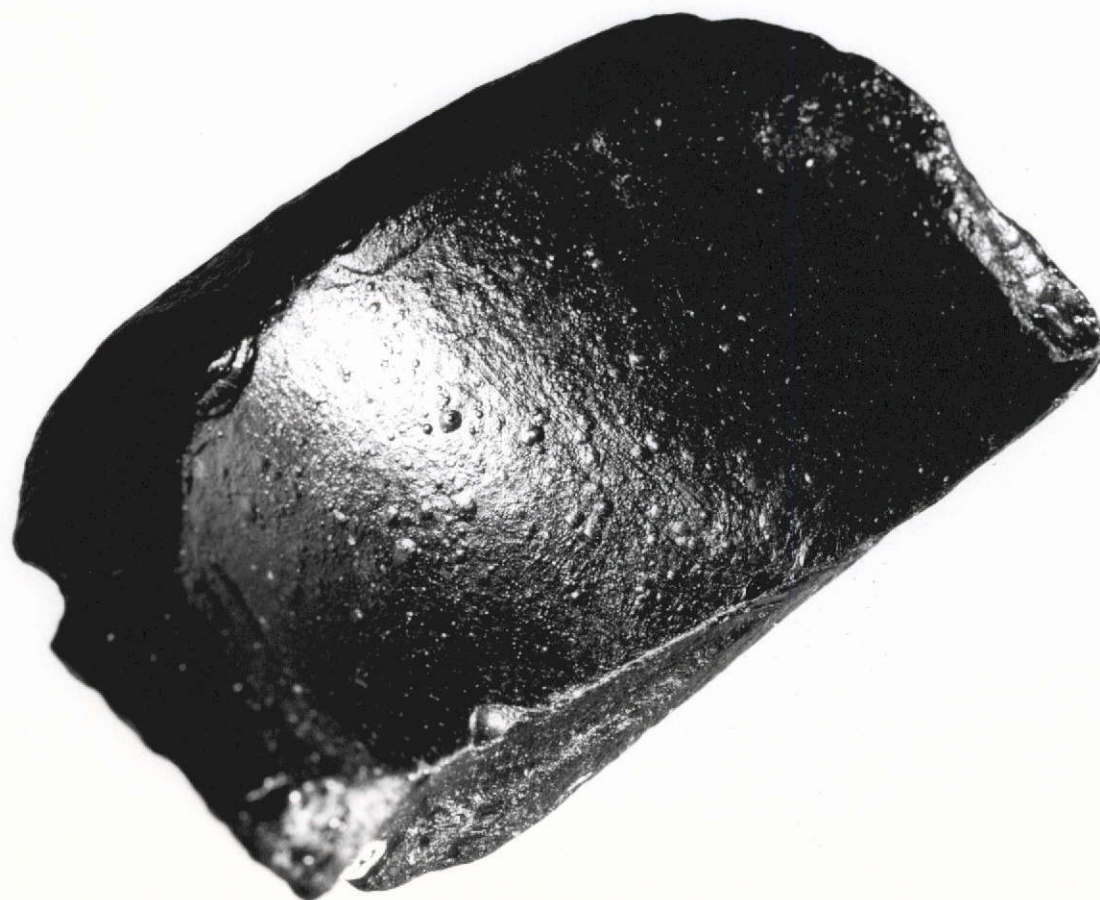
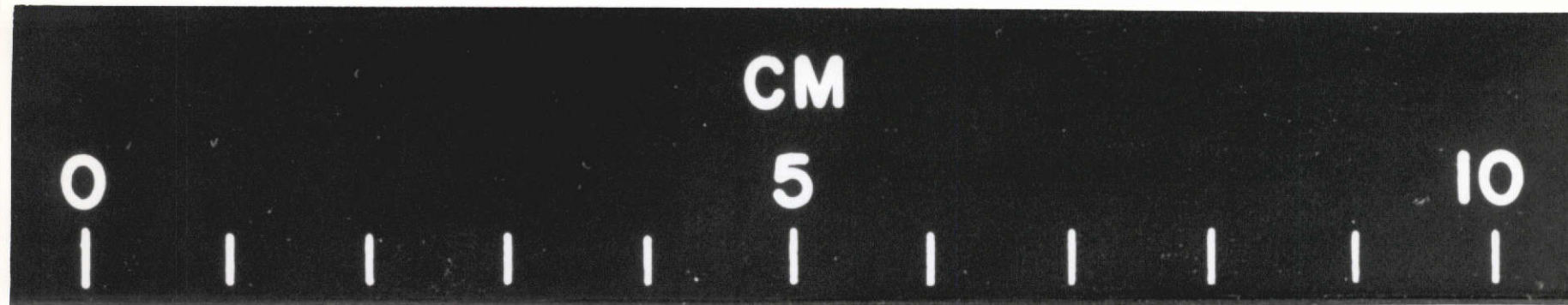


ISABELA, PHILIPPINES



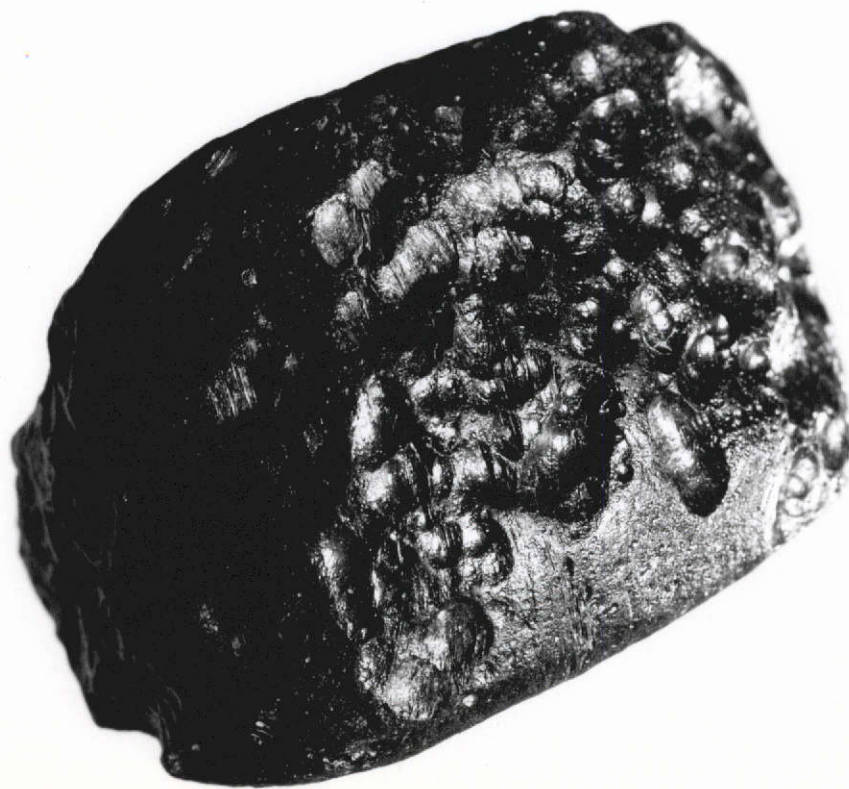
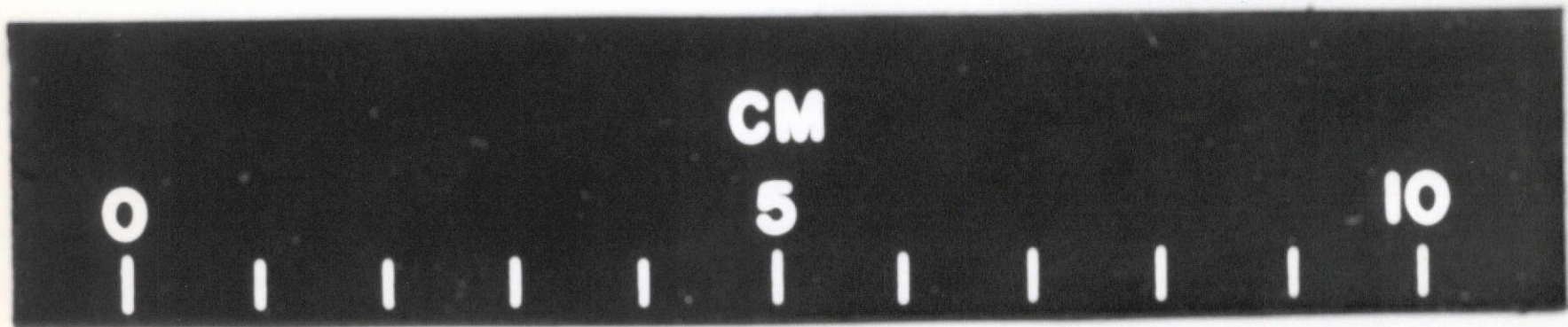
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i - 23 J. A. O. Keefe



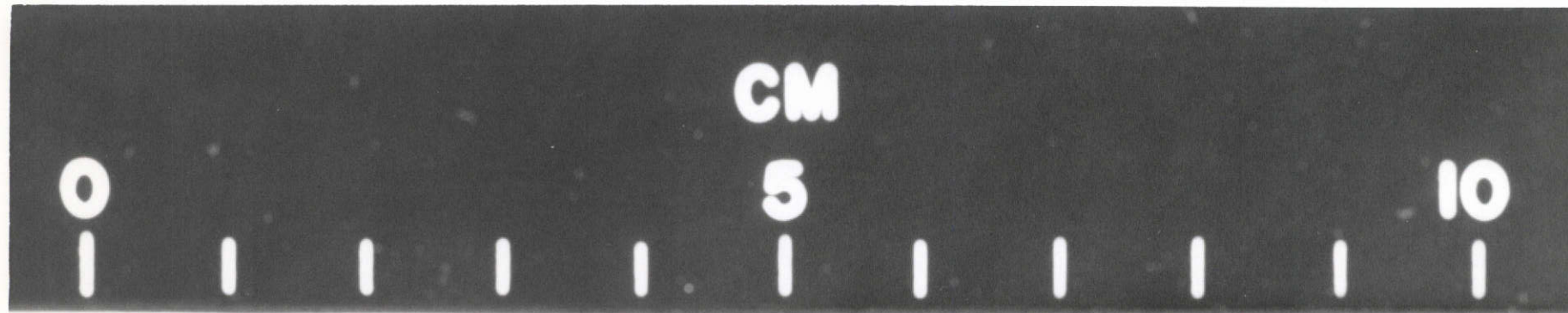
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i-24 J.A. O'Keefe



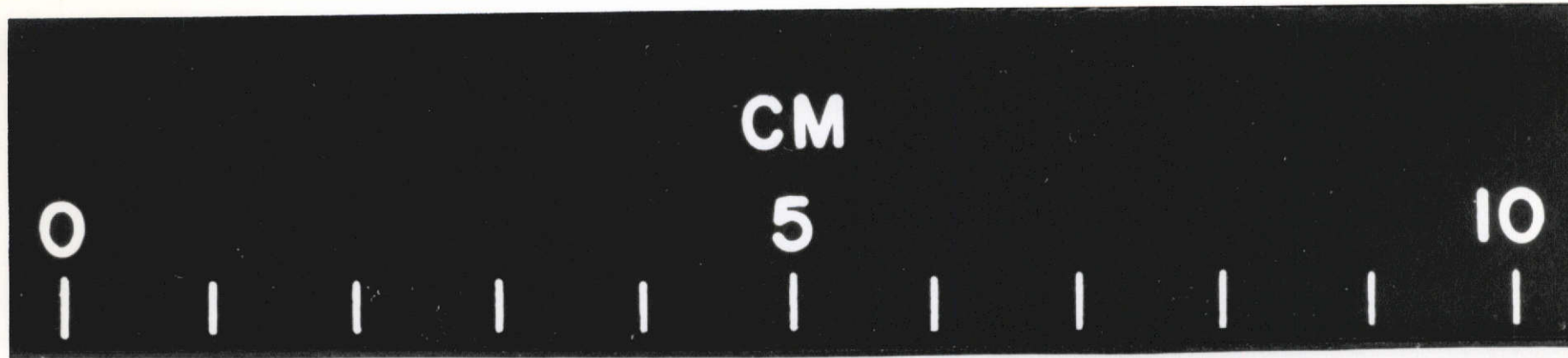
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125 J.A. O'Keefe

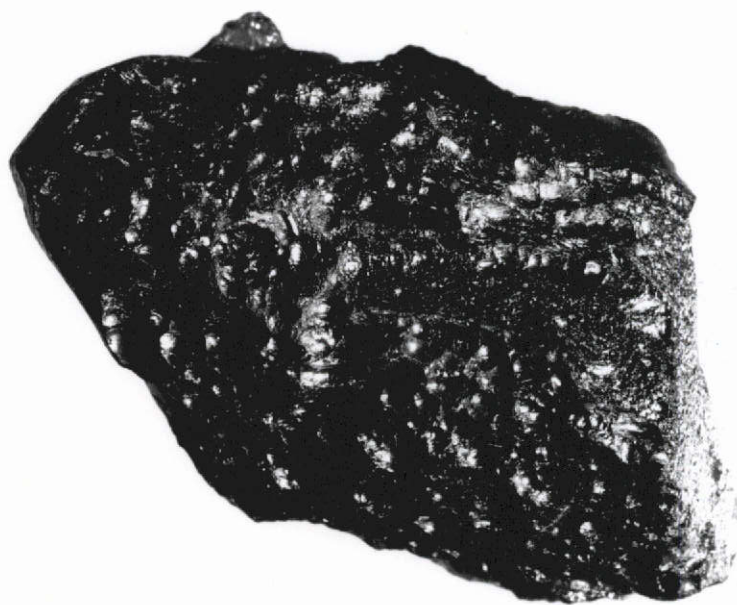
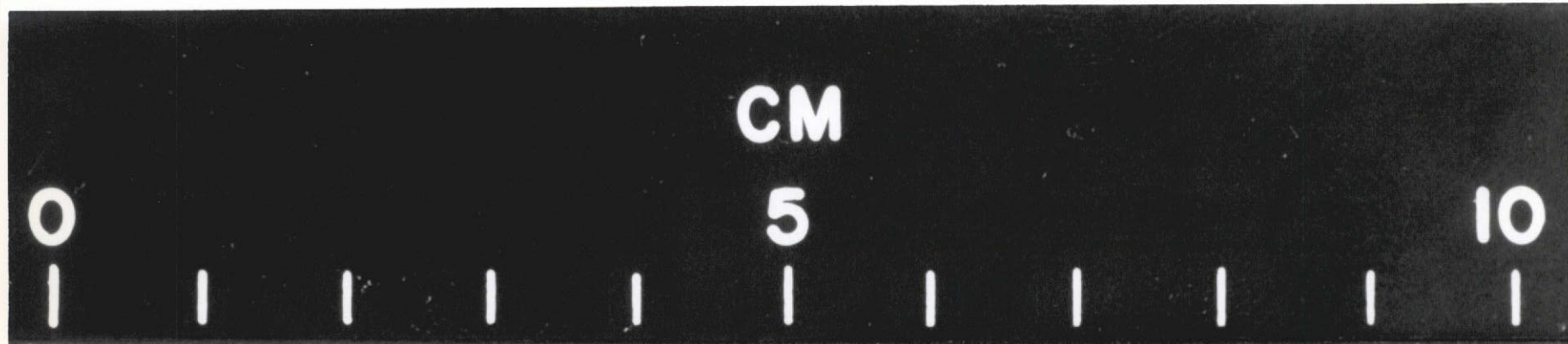


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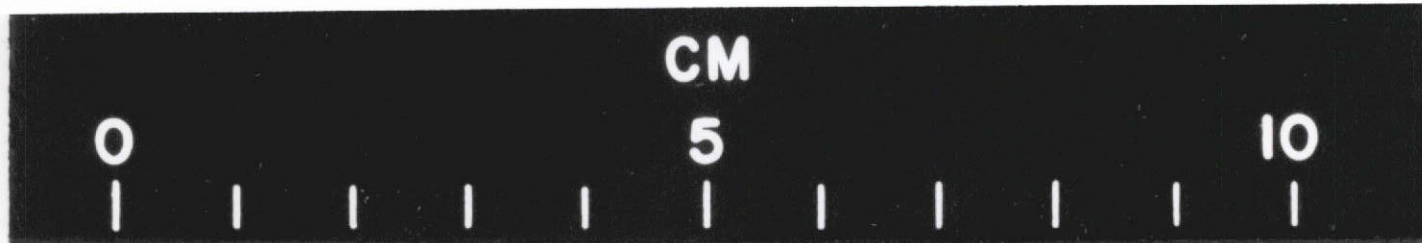
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i-27 J.A.O. Keefe

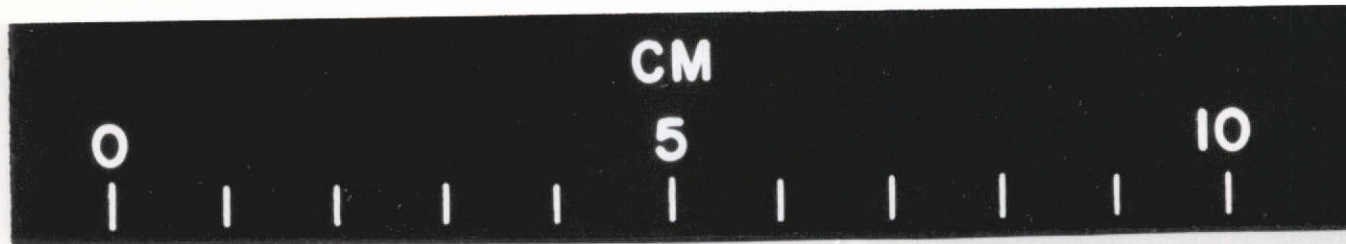


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i - 29 J. A. O. Keefe



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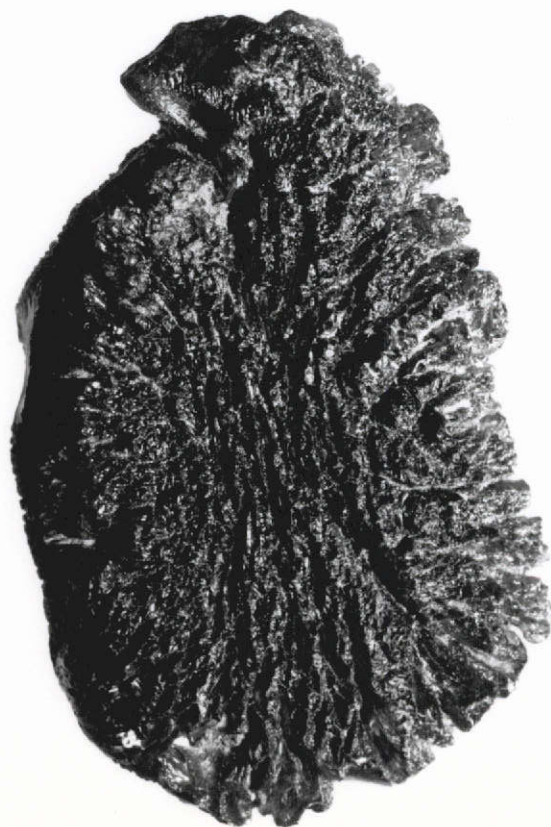
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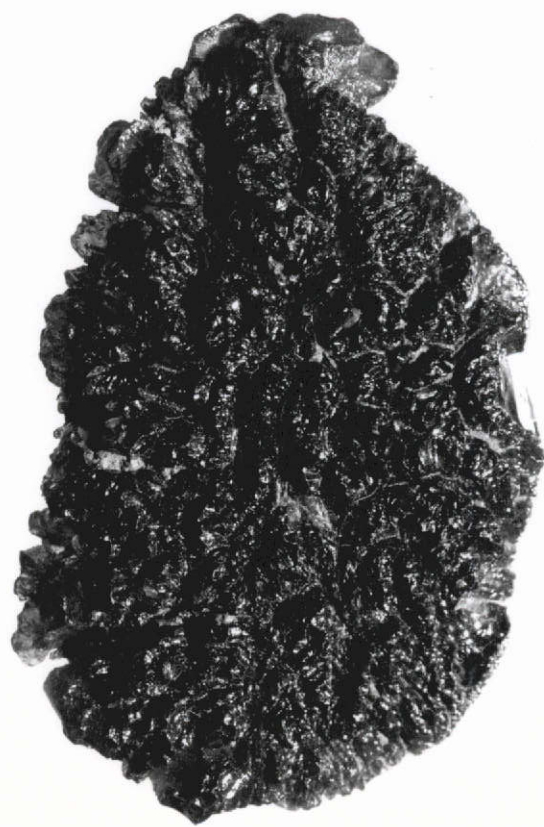
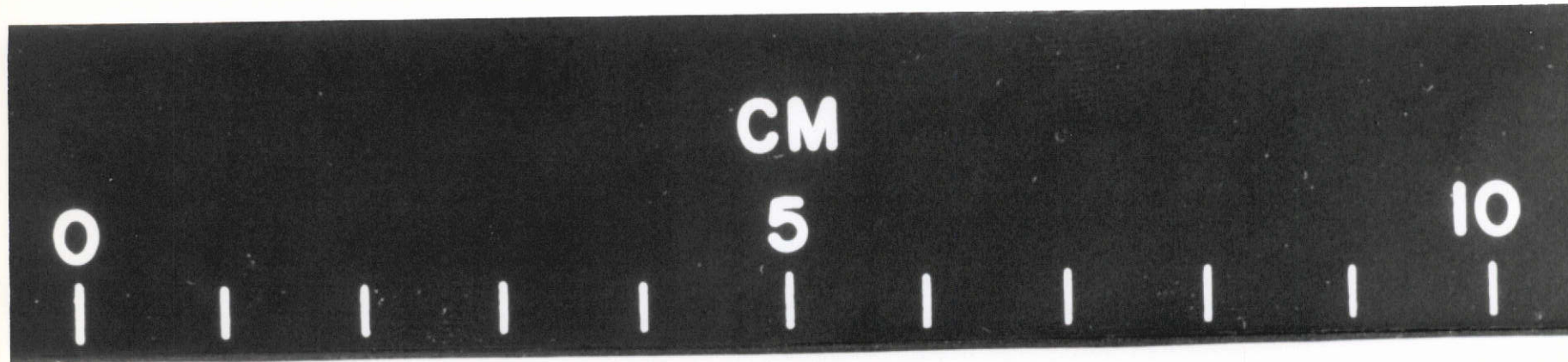
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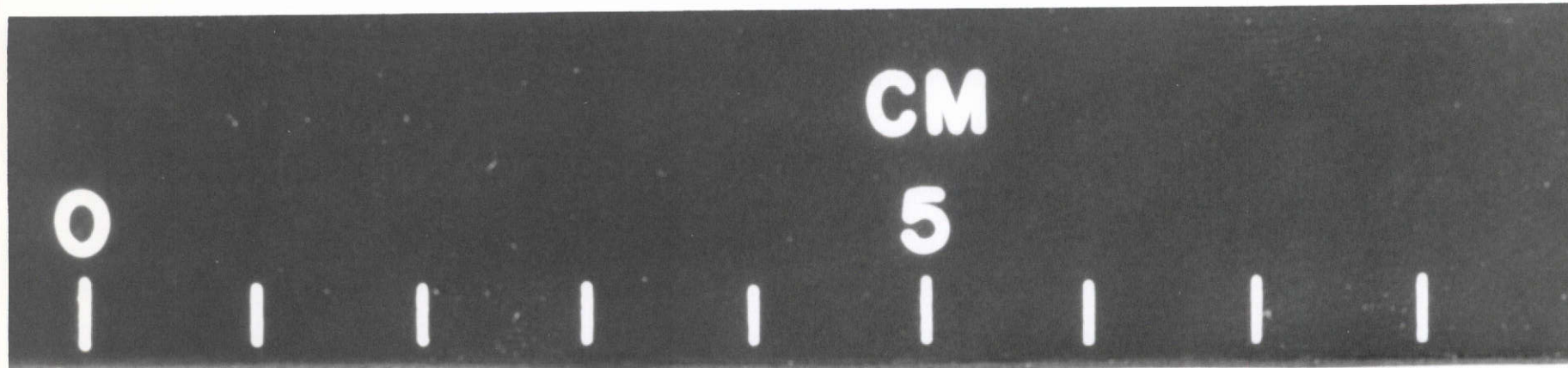


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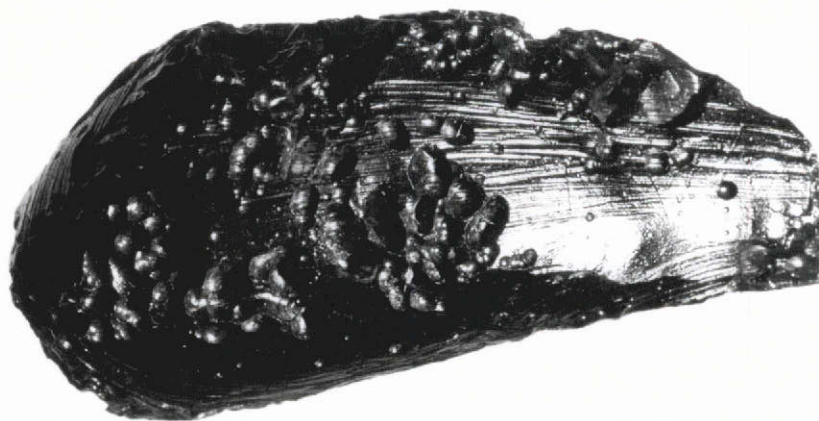
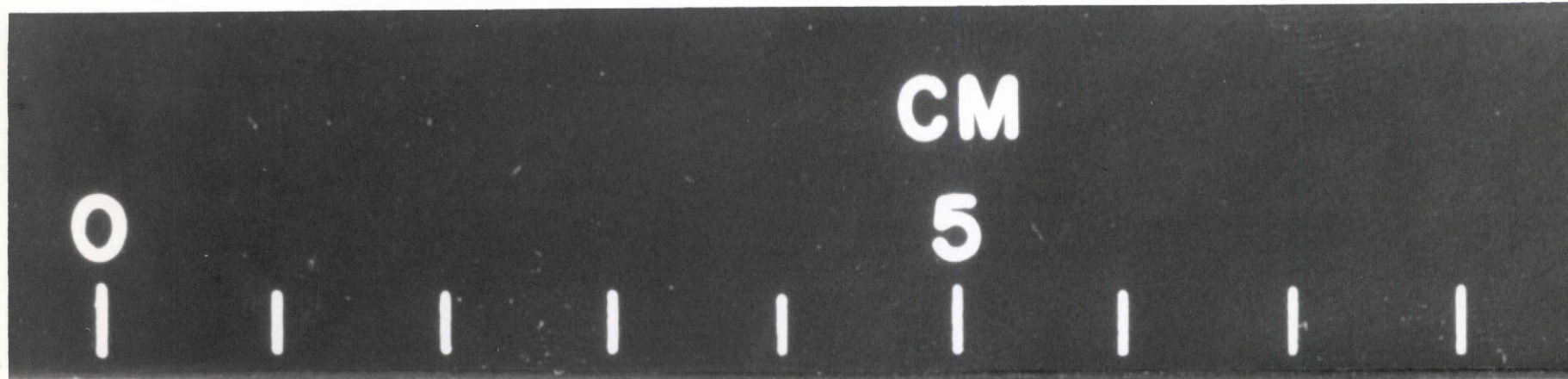
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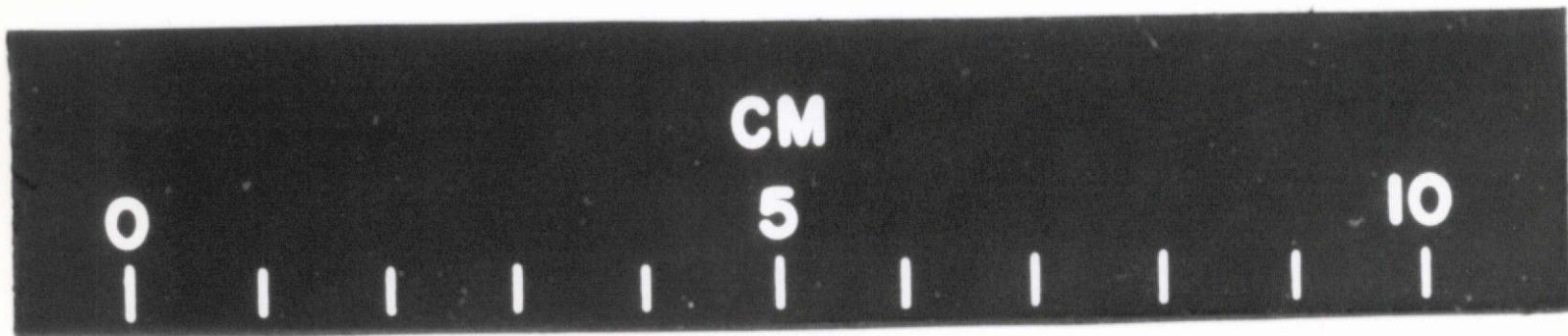
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4-33 John A. O'Keefe

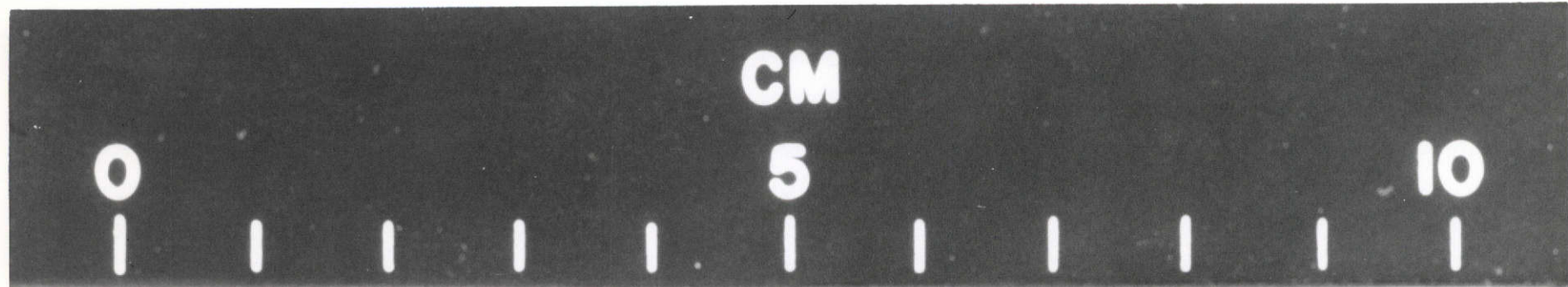


i - 34 John A O'Keefe



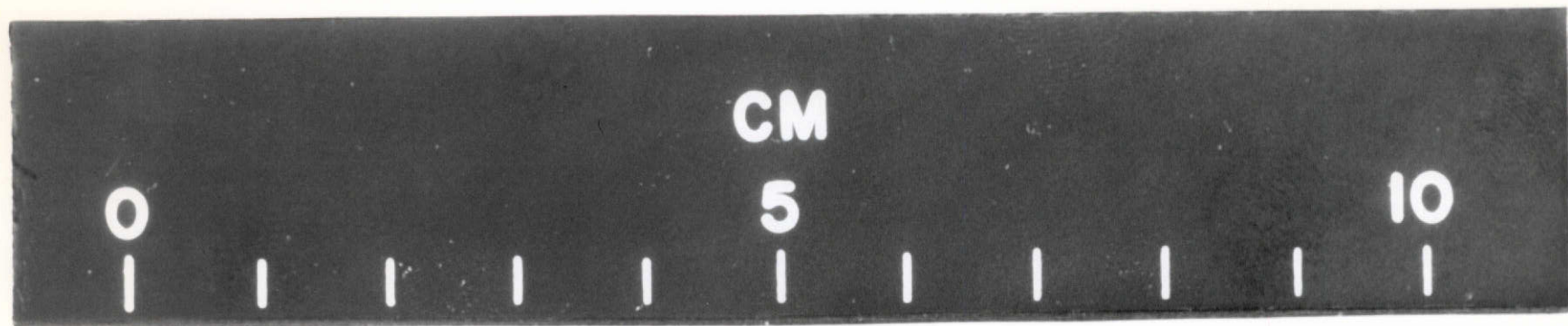
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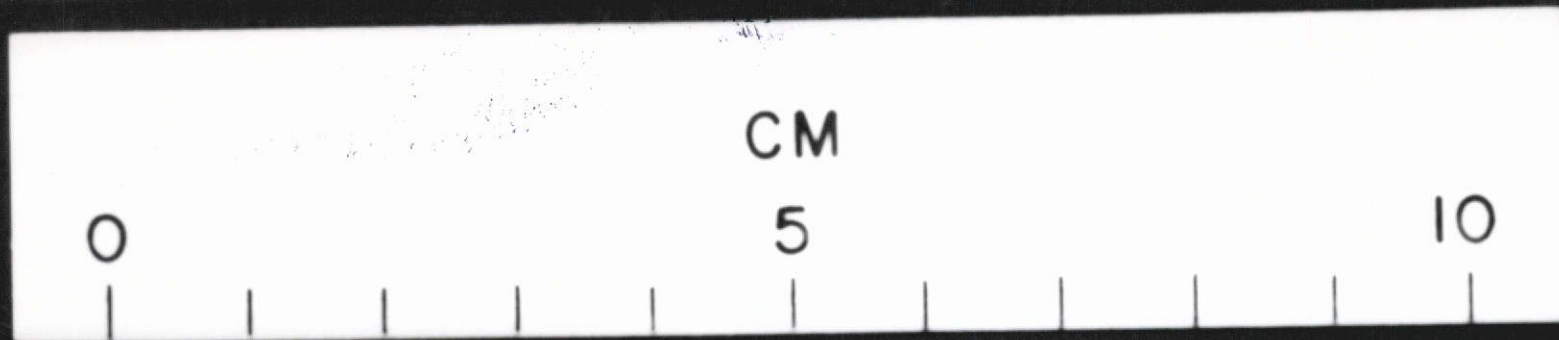
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i - 36 John A. O'Keefe



i-37

i-37 John A. O'Keefe



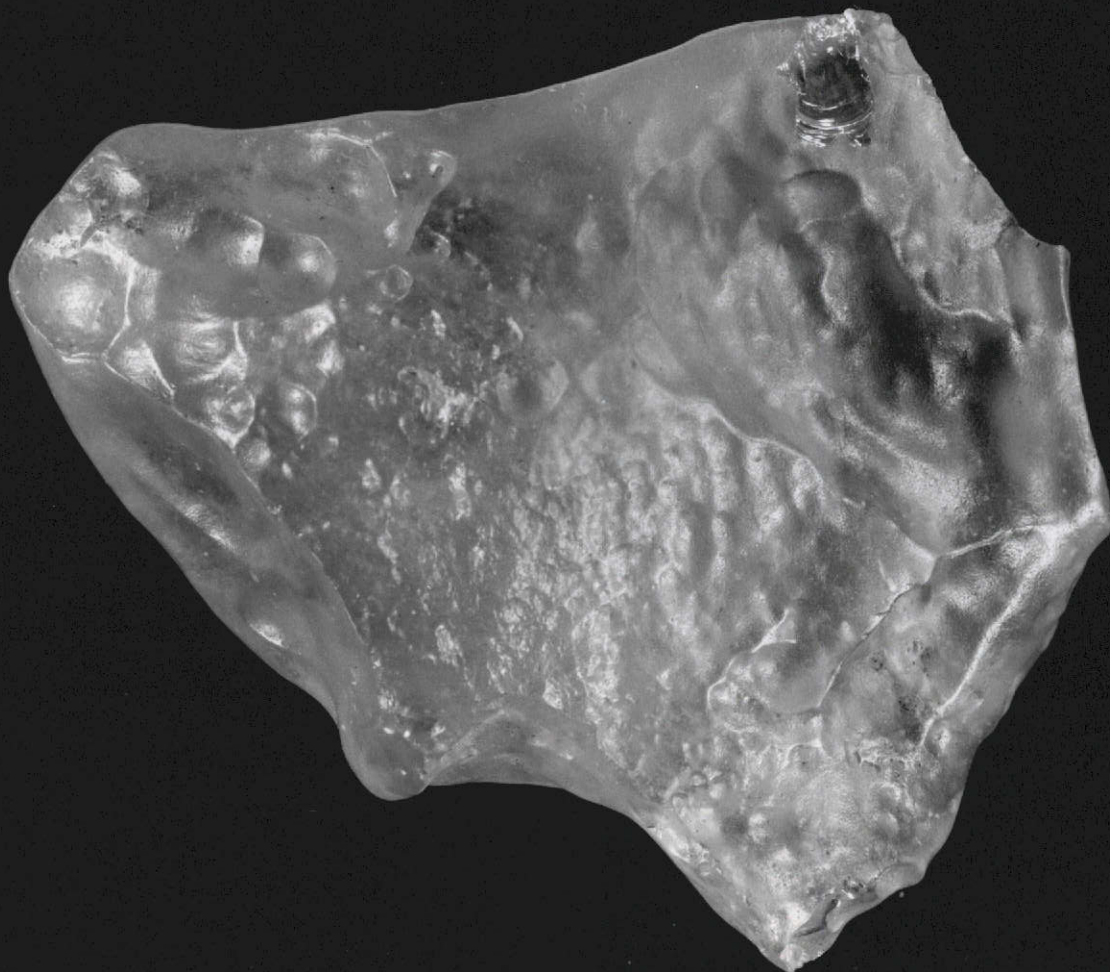
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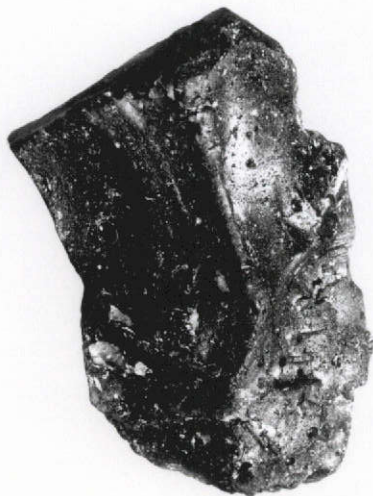
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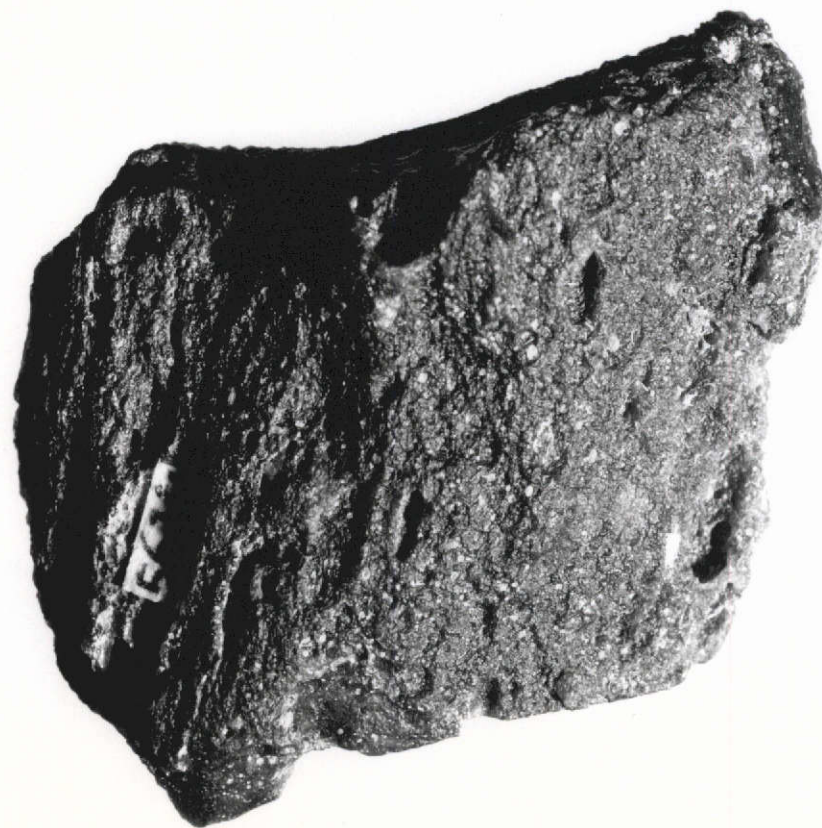
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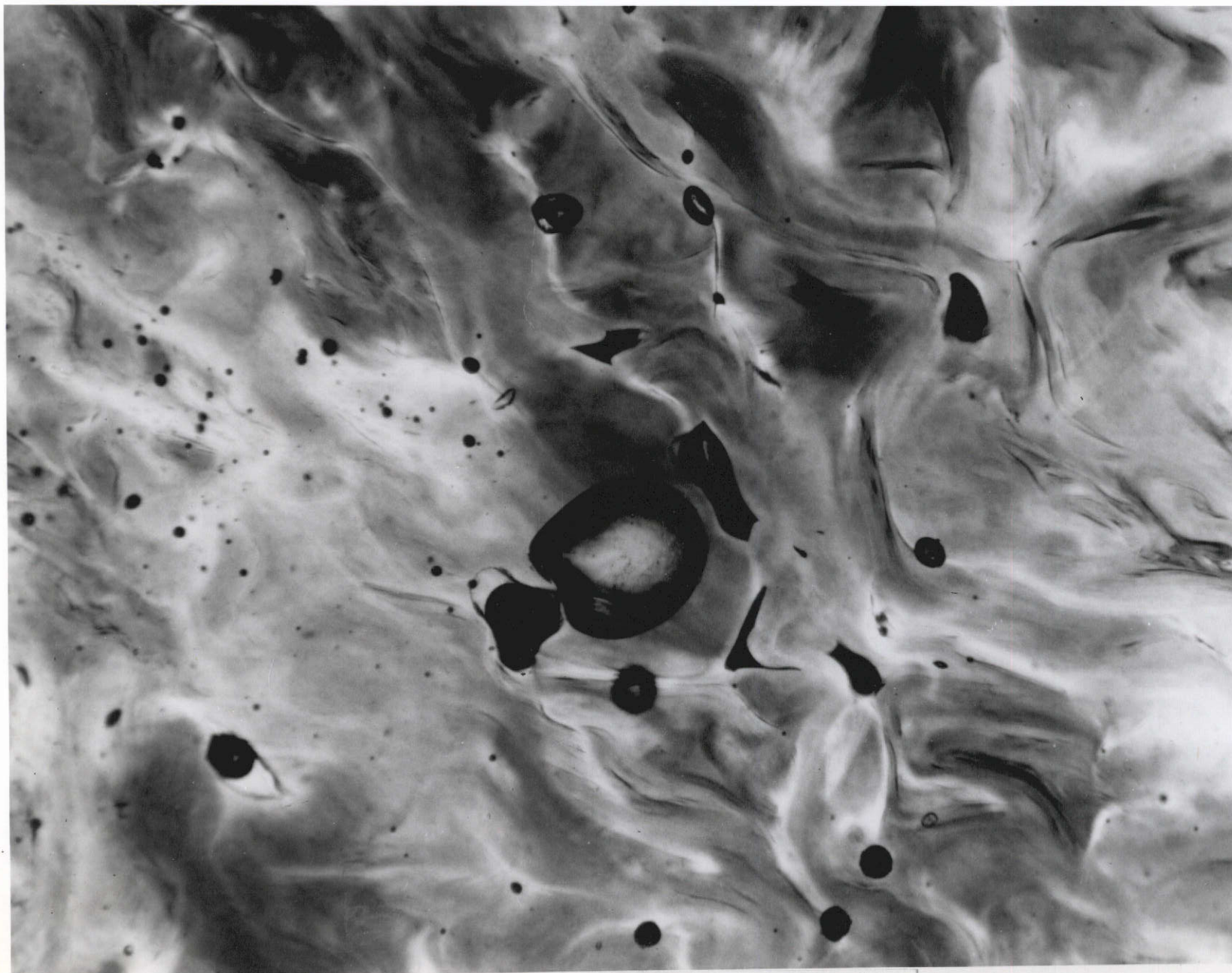
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i-41 John A. O'Keefe



i-42

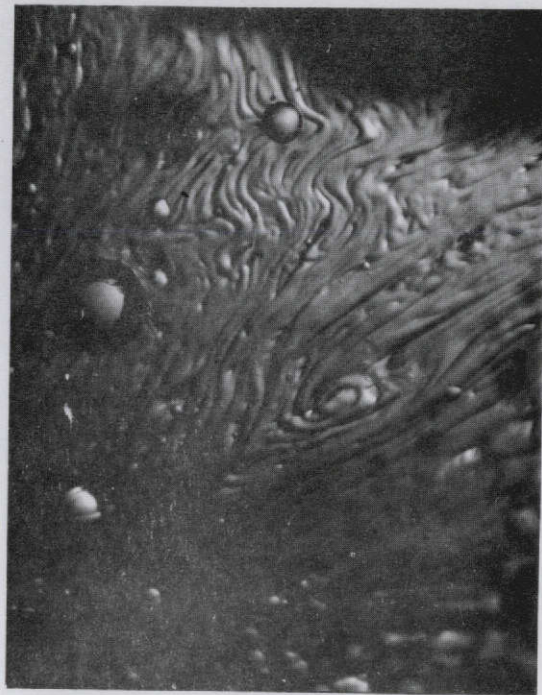
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NASA G-66- 3977

0 100 μ m 200 μ m 300 μ m 400 μ m

i-43 John A. O'Keefe



0.4 mm

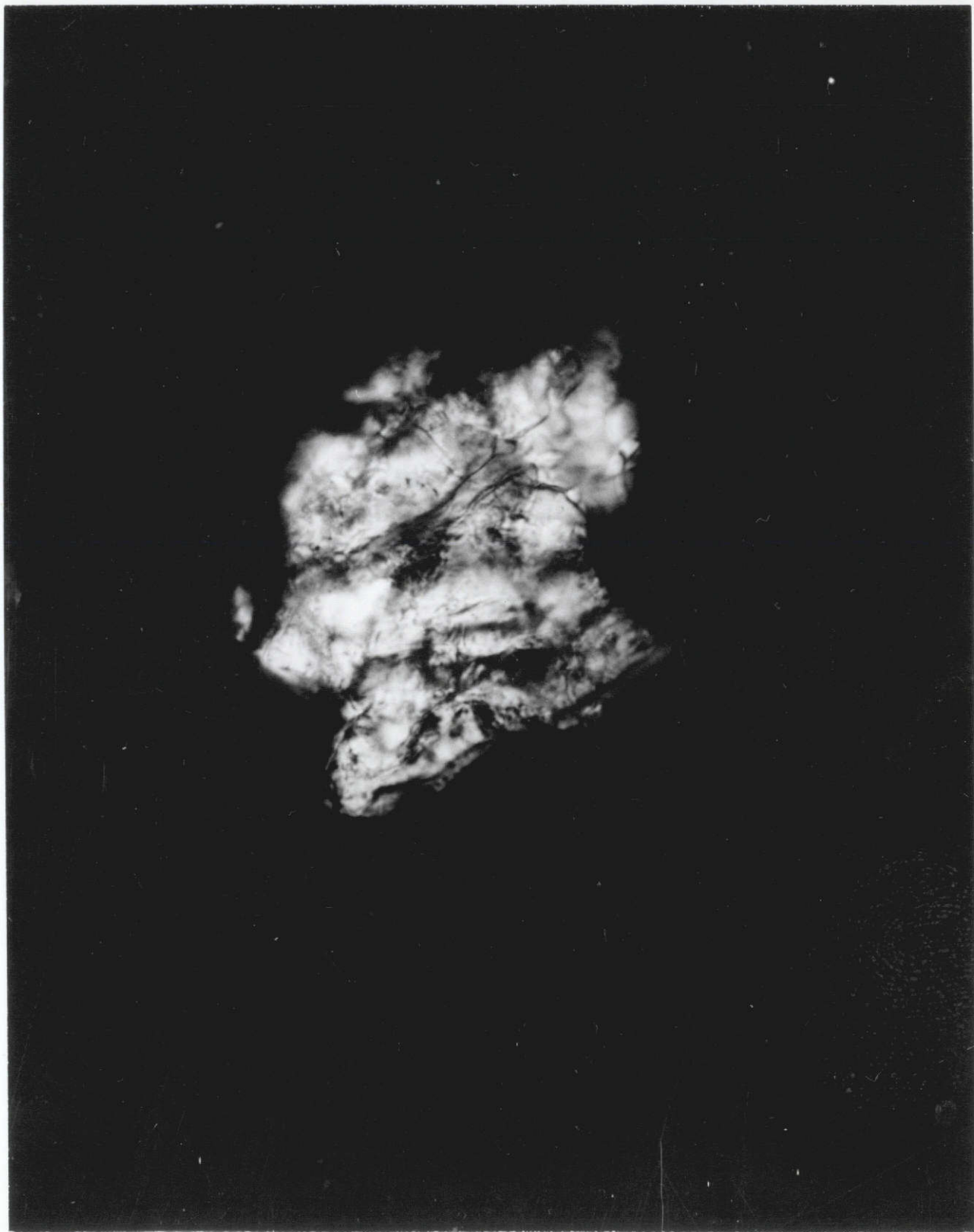
Fig. 15

i - 44 John A. O'Keefe



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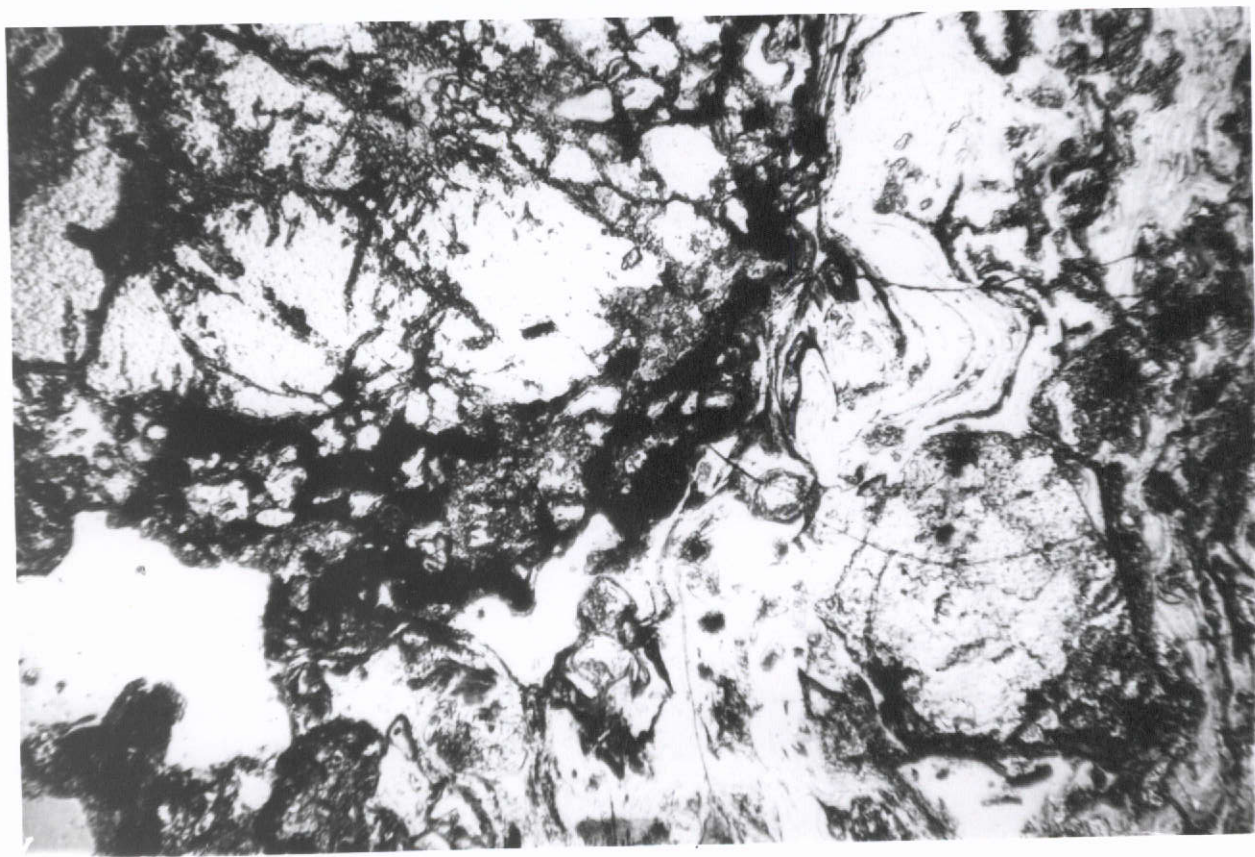
J. A. O'Keefe



0 100 200 μm

i-46

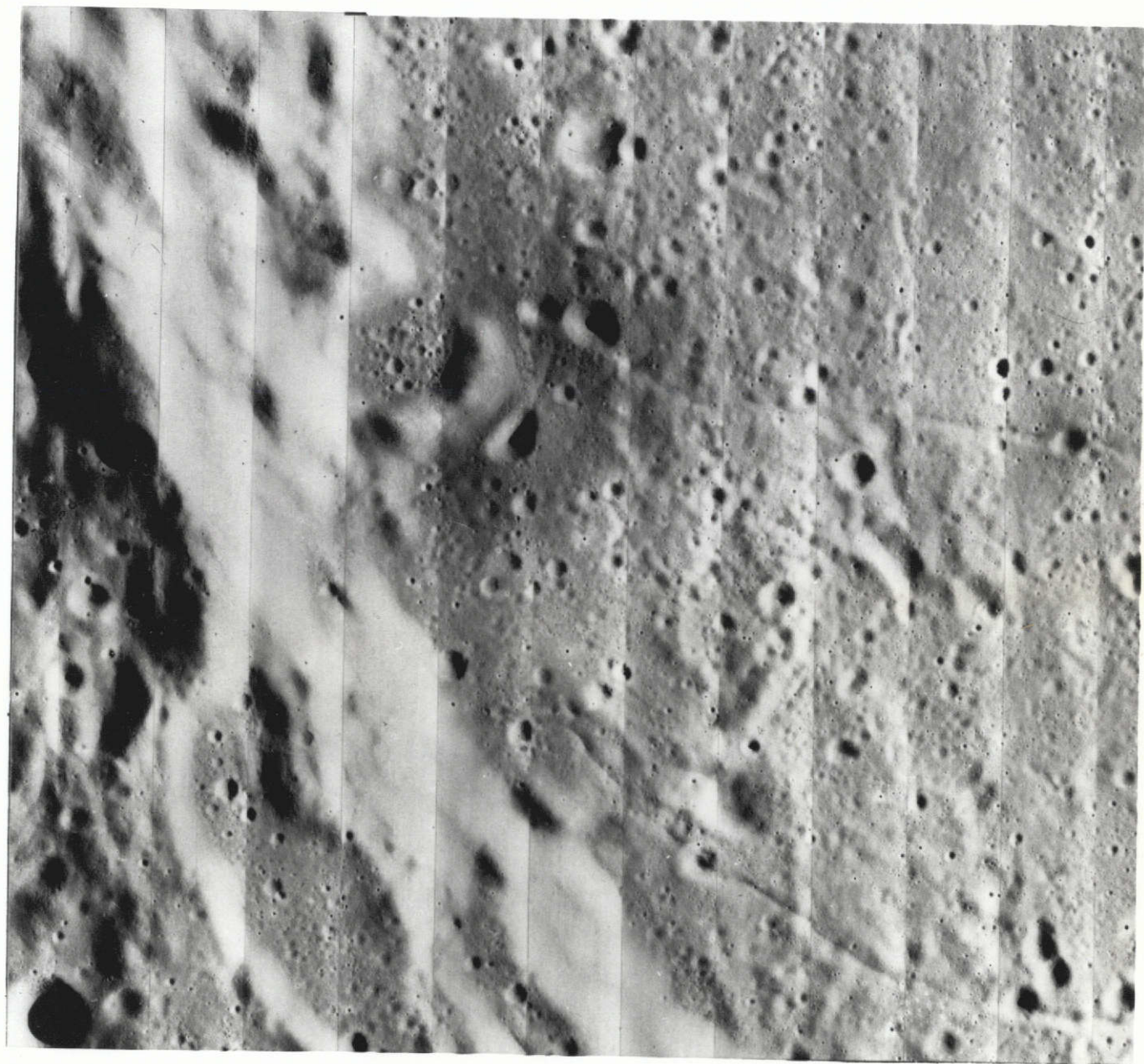
i-46 John A O'Keefe



i-47

x-47

J.A. OKeh



0 10 20 30km

L-48

John A. O'Keefe